TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

ARTO AHLSTEN

CONDITION MONITORING APPLICATIONS OF CRUSHING PLANT

Master of Science thesis

Examiner: prof. Matti Vilkko
Examiner and topic approved by the
Faculty Council of the Faculty of
Engineering Sciences
on 5th October 2016

ABSTRACT

ARTO AHLSTEN: Condition monitoring applications of crushing plant
Tampere University of technology
Master of Science Thesis, 59 pages, 3 Appendix pages
October 2016
Master's Degree Programme in Automation Technology
Major: Process Control
Examiner: Professor Matti Vilkko

Keywords: Condition monitoring, vibration measurement

Effective use of machinery and maintenance planning requires improving of situational awareness and knowing the condition of the machinery. In mineral and aggregate industry, the maintenance is traditionally performed according to fixed time intervals or when the machines break down. One implemented solution for improving situational awareness is different kind of remote monitoring solutions. Knowing the condition of the machines improves the up-time and helps to prevent unexpected failures of the machines that work in difficult conditions. There are various condition monitoring products and services on the market, but they may not fulfil directly all of the requirements of this industry. It may therefore be a risk that the condition monitoring may not be comprehensive enough, if they are implemented with those commercial services.

The goal of this work is divided in three research questions. The focus of the work is on the first one. The question number one is associated with searching of condition monitoring applications, which are application specific for mineral and aggregate industry. In this context, this work reviews different condition monitoring methods, but the actual measurements are implemented by using vibration sensors. The found application specific condition monitoring methods are tested by designing and implementing measurement setup. The measurement setup is installed on a mobile crushing unit – Metso Lokotrack LT106. The measurement setup includes measuring of machine orientation, monitoring of a frame bearing of the crusher and monitoring vibration of machine's main conveyor. The used data-analysis methods are calculating the machine frame orientation by using the measured direction of gravity, monitoring of vibration root-mean-square velocity, envelope analysis of bearing high-frequency vibration and analysis of vibration frequency spectrum. The second research question estimates the minimum hardware requirements for the measurements, so that the desired phenomena can be reliably detected. The third question is to assess the economic feasibility of the selected measurements.

Based on the results of this work, the current single point measurement of unit orientation is insufficient solution. Elastic frame may twist too much during use of the machine, and the operator may not notice it. On the other hand, inclination of the machine may change excessively during the use, if the ground under the machine sinks. In case of the crusher frame bearing, the result of envelope analysis indicates developing faults in a rolling element and inner race of the bearing. In turn, monitoring of the vibration root-mean-square velocity of the main conveyor does detect excessive vibration during the monitoring period, which is quite expected result, because the conveyor is accurately designed by using Finite element method. Based on the results, the orientation of the machine would be worthwhile to implement as commercial product, as well as the crusher bearing condition monitoring.

TIIVISTELMÄ

ARTO AHLSTEN: Murskainlaitosten kunnonvalvontasovellukset
Tampereen teknillinen yliopisto
Diplomityö, 59 sivua, 3 liitesivua
Lokakuu 2016
Automaatiotekniikan diplomi-insinöörin tutkinto-ohjelma
Pääaine: Prosessien hallinta
Tarkastaja: professori Matti Vilkko

Avainsanat: Kunnonvalvonta, tärinämittaus

Koneiden tehokas käyttäminen ja huoltojen suunnitteleminen vaativat tilannetietoisuuden parantamista ja koneen kunnon seuraamista. Kaivos- ja maanrakennusalalla huollot on perinteisesti suoritettu aikaan sidottujen huoltovälien mukaisesti tai koneen hajotessa. Tilannetietoisuutta on pyritty parantamaan erilaisilla etäseurantaratkaisuilla. Koneen kunnon tunteminen auttaisi selkeästi parantamaan käytettävyysaikaa ja välttämään rankoissa olosuhteissa toimien koneiden odottamattomia vaurioita. Markkinoilla on olemassa erilaisia valmiita laitteita- ja palveluja kunnonvalvontaan, mutta ei ne eivät välttämättä täytä kaikkia tämän sovellusalueen tarpeita, joten kunnonvalvontajärjestelmä saattaa jäädä niillä toteutettuna vajavaiseksi.

Työn tavoite on jaettu kolmeen tutkimuskysymykseen. Painopiste on kysymyksessä numero yksi. Kysymys liittyy sellaisten kunnonvalvontasovellusten etsimiseen, jotka ovat sovelluskohtaisia kaivos- ja maanrakennusalan laitteisiin. Tähän liittyen työssä esitellään kunnonvalvonnan eri menetelmiä, mutta varsinainen mittaus- ja tutkimustyö tehdään käyttäen värähtelymittauksia. Löydettyjen sovelluskohtaisten menetelmien testaamiseksi työssä suunnitellaan ja rakennetaan sopiva mittausjärjestelmä. Mittauskohteena on tela-alustainen murskainlaitos Metso Lokotrack LT 106. Koneesta mitattavia asioita ovat rungon asento, murskaimen toisen runkolaakerin kunto sekä pääkuljettimen värähtely. Käytettyinä menetelminä ovat asennon laskeminen maan vetovoiman aiheuttaman kiihtyvyyden suunnan avulla, värähtelyn nopeuden tehollisarvon seuranta, laakerin korkeataajuisen värähtelyn verhokäyräanalyysi sekä värähtelyn taajuustason spektrin analysointi. Toisessa tutkimuskysymyksessä arvioidaan laitteiston minimivaatimuksia, joilla löydetyt mittaustavat ja ilmiöt voidaan luotettavasti tunnistaa. Kolmannen tutkimuskysymyksen tarkoituksena on arvioida löydettyjen menetelmien tuotteistamisen taloudellista kannattavuutta.

Tulosten perusteella huomataan, että koneen asennon mittaaminen yhdestä pisteestä on riittämätön ratkaisu. Joustavan rungon ansiosta runko voi mennä murskaimen käytön kannalta liian kieroon, eikä käyttäjä välttämättä huomaa sitä. Toisaalta koneen kallistus voi käytön aika muuttua liialliseksi alustan painautumisen vuoksi. Murskaimen runkolaakerin kunnon arvioimisessa huomattiin verhokäyräanalyysin perusteella alkavia vikoja laakerin rullassa sekä sisemmässä laakerin kehässä. Kuljettimen värähtelyn tehollisarvon seurannassa ei huomattu vaarallisen suuria värähtelyn arvoja, mutta tulos on sikäli odotettu, että kuljetin on suunniteltu tarkasti FEM-laskentaa käyttäen. Tulosten pohjalta koneen asennon mittaaminen olisi kannattava toteuttaa, kuten myös murskaimen laakerien kunnonvalvonta.

PREFACE

This work is done as a part of DIMECC S-Step project. The focus of S-Step project is to raise the machine level embedded intelligence to new level, so that fundamental capabilities for independent operations of the machines are increased. Most of the work is done at the Metso Minerals in Tampere. The experiments were performed at Pärhä Oy site.

I wish to express my gratitude to Prof. Matti Vilkko at the Tampere University of Technology and Antti Jaatinen at Metso Minerals Oy for their extremely valuable support and guidance. I would also thank Metso Minerals Oy for opportunity do this work, and especially I would like to thank Pärhä Oy for allowing the experiments on their site. I also express my gratitude to Eero Ahlsten for help with 3D pictures, Paavo Nieminen (Metso Minerals) for help with measurement setup installation, as well as Pekka Itävuo (Tampere University of Technology) and Risto Sutti (Metso Minerals) for guidance, inspiration and co-operation during this work.

Tampere, 26.10.2016

Arto Ahlsten

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating current
AE	Acoustic emission
BLE	Bluetooth Low-Energy
BPFI	Ball Pass Frequency of Inner Race
BPFO	Ball Pass Frequency of Outer Race
CAN	Controller Area Network
DFT	Discrete Fourier transform
CMS	Condition monitoring system
FFT	Fast Fourier transform
FTP	File Transfer Protocol
IC	Intelligent Control system
IR	Infrared
ISO	International Organization for Standardization
MEMS	Micro-electro-mechanical system
MSP	Multi sensor platform
RFR	Rotational frequency of Rolling element
REDF	Rolling Element defect frequency
RMS	Root-mean-square
TI	Texas Instruments
VPN	Virtual Private Network

A	Area between two capacitor electrodes
BD	Bearing ball or roller diameter
$a(t)$	Acceleration of sensor housing
a_x, a_y, a_z	Measured acceleration of sensor measurement axis
C_1, C_2	Capacitances of differential acceleration sensor
d	Initial distance between sensing element and fixed electrodes
F	Force
f_r	Relative rotational speed between inner and outer races of rolling element bearing
i	Imaginary unit
k	Spring constant
m	Mass
n_b	Number of rolling elements per row in rolling element bearing
N	Length of the signal (number of samples)
n, p, j	Indexes
PD	Pitch diameter of rolling element bearing
T	Duration of measurement signal
t	Time
ΔT	Sample interval
V_{out}	Output voltage of capacitive deflection bridge
V_s	Source voltage of capacitive deflection bridge
$v, v(t)$	Velocity of sensor housing
v_{rms}	Root mean square of velocity
x	Displacement of sensing element
$\dot{x}$	Velocity of sensing element
$\ddot{x}$	Acceleration of sensing element

$X[p]$	N-Point discrete Fourier transform of $x[n]$
$x[n]$	Discrete-time signal
$x_{envelope}[n]$	Discrete envelope signal
$Z[p]$	Discrete analytic signal transform
$z[n]$	Discrete analytic signal
$z_{im}[n]$	Imaginary part of analytic signal
$z_{re}[n]$	Real part of analytic signal
β	Contact angle in rolling element bearing
ε_0	Permittivity of vacuum
ε	Relative permittivity of dielectric medium
θ_x, θ_y	Inclination values in degrees
λ	Damping coefficient.

1. INTRODUCTION

In the field of mineral processing, the increasing competition and decrease of commodity prices require reduction of production costs. This sets new demands for monitoring the condition of the process devices. Traditionally, the maintenance in mineral processing industry is performed based on fixed time intervals or reactively. Effective condition monitoring system (CMS) will reduce unexpected failures. Thus it enables possibility to decrease downtime of the plant, schedule maintenance according to need and schedule spare part delivery correctly. Furthermore, too worn parts in process devices will increase energy consumption, so condition monitoring will reduce plant long-term energy consumption.

1.1 Motivation

Aggregates are granular material that are used in a wide range of constructions like railroads, infrastructure and buildings. Aggregates such as sand, gravel and crushed rock are extracted from quarries and pits. In addition, aggregates can be produced from recycled material that are from demolished constructions. In aggregate industry, and in mining industry as well, the product needs to meet application specific requirements. The shape and particle fragmentation related demands can be satisfied by crushing and screening. The material can be comminuted by crushing and different sized particles can be separated by screening. [1] [2]

In Europe, 15 000 companies produced 2,6 billion tonnes of aggregates in year 2013, which means around 15-billion-euro revenue. Those companies employ over 200 000 people and the production of aggregates occurs in 25 000 quarries and pits [1]. The production tonnage and the turnover gives a rough estimate for average income per produced tonne, which is 5,80 €/tonne. In conclusion, it can be said that the profit in aggregate industry comes from high volume production. For instance, the maximum capacity of Lokotrack LT300GPB is 450 tonnes per hour [2] so in worst-case scenario, every lost eight-hour production period means almost 21 000 € lost income.

Crushing plants are divided in two main categories: mobile and stationary. Both plants basically consist of same main devices such as crushers, screens, different kinds of feeders and conveyors that are connected in series or parallel to each other. The main difference is that stationary installed plants require more loading and hauling than mobile plants, because they cannot be moved along the quarry face, but the mobile plants are usually mounted on tracks and can be moved along quarry face. The track-mounted units require caution from the user, because the process devices such as crushers and screen are designed to be placed horizontally on solid surface. The selection of plant setup depends on desired products and capacity. In addition, the feed material characteristics, such as feed fraction, moisture content, material density, crushability and abrasiveness, have an influence on selected setup of process devices also. [2]

From a customer point of view, high volume based production requires that process downtime is minimized. Especially in sites where strict environmental requirements set time limitations concerning of when crushing is performed. Unexpected device failures will lead to extra delay before process is up again, because a bit damaged parts may be easier to change than totally broke down ones, or the feed material may have to be removed manually before repair. Furthermore, the needed spare parts are not always available at the site. When process condition is monitored properly, most of the device faults may be possible to anticipate. When failures are anticipated, the needed parts can be ordered in advance and maintenance can be planned properly. In that case, the time consumption is possible to be decreased and several maintenance actions can be executed at a same time without extra process stops. Respectively, unnecessary maintenance actions can be avoided, because the condition monitoring indicates when maintenance is needed. The second point of view for condition monitoring is to avoid running the process in not advantageous way. These kind of situations may be, for example, resonance in conveyors, excessive wear in crusher wear parts and crusher motor high vibrations. Safety aspect cannot be ignored either. Total device break downs cause exceptional situations in many industrial processes and, in consequence, are favorable possibilities for accidents. These exceptional situations can include dangerous lifts or use of power tools that would not be needed if the maintenance had been made before device break down.

In Metso point of view, the condition monitoring may help to reduce warranty costs also. Even in minor issues, the costs are usually thousands of euros [3]. One reason for this is that, in addition to the spare parts, the costs consist of maintenance personnel travel expenses, and the time spent to identifying and repairing the fault. Condition monitoring, or system monitoring, benefits may be that in addition to the actual fault, the other potential faults can be repaired during one service visit. This will reduce the unexpected process stops and downtime also, so the problems do not affect the customer so much, which is good for the reputation of Metso. Other benefits for Metso are that system monitoring may give more details about failure root-causes and possible improper use of the devices, or it can be used to prevent misuse. These kind of misuse situations include, for example, that Lokotrack is placed on inclined surface or the crusher is used with too small setting. In these situations, the resultant crushing force resultant differs from the design and the force may be too great.

1.2 State of research

Condition monitoring methods are widely researched in many industries and several companies like Metso, Valmet, SKF, Rockwell Automation and Siemens have their own condition monitoring systems for wide range of industries. For instance, Metso ScreenWatch is condition monitoring system for screens, which includes real-time analysis of performance and bearing condition. [4] [5] [6]

Several ISO-standards (International Organization for Standardization) covers condition monitoring related standards. The standards discuss with, for example, vibration and thermography based condition monitoring, sensor mounting, data-analysis and how the measurement should be implemented in certain type of machines. Examples of those ISO-standards with short description:

- ISO-5348: Mechanical mounting of accelerometers [7]
- ISO-7919 series: Measurements of rotating shafts and evaluation criteria [8]
- ISO-13373 series: Vibration condition monitoring [9]
- ISO-13379 series: Data interpretation and diagnostics techniques [10]
- ISO-10816 series: Machine vibration by measurements on non-rotating parts [11]
- ISO-10817 series: Rotating shaft vibration measuring systems [12]
- ISO-18434 series: Thermography based condition monitoring [13]

In scientific research, different kind of condition monitoring methods are researched. In particular, the wind power plant condition monitoring is strongly represented. Wind power plant may be analogous to mineral and aggregate processing plants to some extent, because both runs in difficult and variable conditions. In addition, the load and speed of the machines changes often. For example, mechanical structures, bearings and gearboxes are measured in many different ways. Vibration is one of the most used measurement in condition monitoring. Other used measurements are, for example, acoustic emission, strain and temperature. Chapter 2.2 presents an overview of existing condition monitoring methods. [14] [15]

In addition, scientific research has also shown results from condition monitoring methods that uses, for instance, fuzzy learning, unscented Kalman filter based condition monitoring for hydraulics and cluster analysis utilizing CMS for wind power plants. The fuzzy learning based method improves the performance of the CMS in uncertain environments by making the CMS less sensitive to uncertainties and noise. In turn, the Kalman filter based method is used to detect internal and external leakages of a hydraulic actuator. The method is based on residual of a measurement from real process and dynamic model output of the process. By using the unscented Kalman filter the CMS can take into account the non-linearity of the process and the CMS is more robust against noise. In turn, the cluster analysis based CMS is a plant level system, that uses real process data for machine learning to learn the normal behavior of the plant. The fault detection is based on anomalies between learned normal behavior and online process data. [16] [17] [18]

1.3 Research questions and goals

The goal of this thesis is to map feasible condition monitoring applications that increase situational awareness of the crushing process equipment. More intelligent machines with increased situational awareness offers possibilities to make maintenance and control actions more effectively. Comprehensive fault models and software development are out of the scope of this work. However, the rational selection of measurement point, measured quantity and data analysis method are critical in terms of finding the fault models with reasonable cost, so that will be taken in account. The goal is divided into three research questions that parse the goal in smaller parts.

Q1. What kind of potential application specific phenomena, such as machine misuse or evolving faults, can be detected from the unit by measurements?

Q2. What are the minimum requirements for measurement system to detect the phenomena that occur in the unit?

Q3. Which of the measurements are feasible to use in economic sense?

The first question considers the faults and misuse detection from the measurement signals. The answer of that question includes the selection of measured quantity and measurement setup together with suitable data-analysis method. In the second question, the intention is to define the minimum requirements for the measurement hardware so that different phenomena can still be detected reliably. The result of that question can be used to estimate the technical requirements of the measurement system for commercial use. This is especially interesting in wireless technology and in use of low price segment components point of view. The third question is associated with commercial feasibility of the measurements.

1.4 Structure of the thesis

This thesis is divided in six chapters. The second chapter presents the used methods including a new product development model that is used as systematic approach to selecting the essential measurements. Furthermore, the second chapter gives an overview of existing condition monitoring methods, and presents the measurement and data-analysis methods. The third chapter includes the measurement setup definition and the experiment description. The fourth chapter deals with the results of the experiment. In the fifth chapter, the results of the experiment are analyzed. The sixth chapter sums up the whole thesis and provides suggestions for further development.

2. METHODS

This chapter presents the methodology used in this work. At first, the stage-gate -model is presented and existing condition monitoring systems are shortly introduced. Furthermore, the used sensors and data-analysis methods of this work is presented.

2.1 New product development: Stage-gate -model

Stage-gate -model is a system for new product development. The model consists of gates and states, which are designed to guide the development of a new product. Different stages are intended to ensure that right amount of effort is used and right actions are made at right phase of the project. A clear process helps both project workers and managers. The gates act as quality control so that the process is evaluated based on predefined criteria. The criteria are usually divided in *have to meet* and *should meet* type of criteria. According to the evaluation, a decision need to make whether the project is rejected or the current stage is iterated or the project is continued to the next stage. Figure 1 presents the basic form of the model, which can be modified depending on the process and the product characteristics. [19]

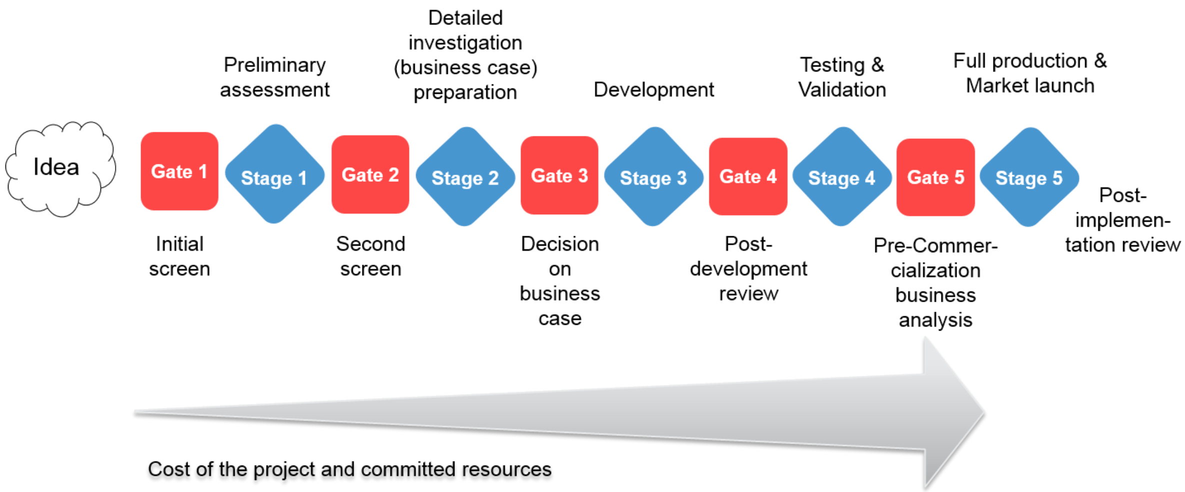

Figure 1.*Stage-gate -system for new product development. [19]*

As Figure 1 presents, the new product development begins from a new product idea or need that needs to be satisfied, and the process proceeds through the gates and stages. Each gate and stage are presented in more detail in the following paragraphs.

At gate 1, the new idea or ideas are evaluated according to the *have to meet* and *should meet* criteria. The criteria help to focus on the relevant issues such as synergy with the firm's core business, idea's potential competitive advantage, market interest and potential opportunity. Financial issues are not taken into account at this gate. If the project is decided to continue after gate 1, the project continues with stage 1. This stage consists of quick and inexpensive study that deals with the financial and technical merits of the project. Financial study can consist of interviewing potential customer, book study or concepting that map the size, potential and acceptance of the market. Technical study consists of technical feasibility related issues such as needed resources or whether the product can be developed and manufactured within reasonable cost and time consumption. [19]

At gate 2, the idea is re-evaluated by using the knowledge that has been gained at phase 1. The evaluation uses same criteria than at gate 1, but financial aspect is taken into account also. Financial evaluation should be made with rough evaluation. If the project passes the gate 2, the comprehensive definition of the project is made at stage 2. That stage expands the feasibility study of the project, and the development plan and the drafts of operations and marketing plans are created. In financial feasibility study, the needs and demands of potential customers are mapped more comprehensive. Competitive analysis should also be made, so that competitive situation and the weaknesses of existing solutions are known. Technical feasibility study may include light concept testing and preliminary designing. Finally, the legal feasibility of the project is examined and more comprehensive financial analysis is made. Legal feasibility is studied so that it can be detected whether the potential solution does break any laws, patents or copyrights, and the financial analysis gives information to gate 3. [19]

Gate 3 determines if the project is turned to business case or not, which means that the amount of resources required by the project are about to grow heavily. The gate starts with re-evaluation of the project based on gate 2 criteria. The second task is to check the quality of actions that have been made at stage 2 so that the results are reliable and realistic. The last thing at gate 3 is to check and approve the plans that have been made in stage 2. The project moves to the development stage, that is, stage 3. The development stage includes the development of product itself, but development of testing, marketing and operations plans also. [19]

Gate 4 assesses the success of the development stage. The quality of the development stage and project attractiveness in both the company and the potential customer point of view is evaluated. The financial feasibility is re-evaluated, because development phase should offer more precise information, for example, from production and marketing costs. According to these evaluations, test and validation plans are confirmed, and marketing and operations plans are reviewed. Passing the gate 4 starts the stage 4, which is the validation phase of the whole project. Validation includes a wide range of different kind of testing and evaluations, that test product viability related to economics, production process and customer acceptance. Product quality and performance are tested with in-house tests and field-tests. Potential customers may participate in field-testing so that customer attractiveness can be observed. In turn, manufacturing chain, production cost and production rate can be tested via pilot production. Before financial feasibility is re-evaluated with more accurate data, the launch plan, market share and revenues are tested with test sell. [19]

The decision whether the product is commercialized is made at gate 5. The gate focus on the quality and results of validation process. The decision is made based on the results and the quality check ensures that right methods are used in validation. Operations and marketing plans are checked and approved also at this gate. The last actual stage, that is stage 5, marketing and operations plans are put into action. [19]

The new product development process ends after commercialization and the product is moved to support and maintenance phase, after which responsibility for the product is moved away from research and development team. After that, the whole new product development process is reviewed. After the project, it is fruitful to compare differences between estimated and actual costs, time consumption, results and revenue for instance. It is important to consider the strengths and weaknesses of the project. All of these factors can be used for the development of working methods and processes. [19]

2.2 Overview of existing condition monitoring systems

Condition monitoring has been applied in many different industries, such as energy production, mining and construction, marine and pulp & paper. In general, the observed components or phenomena are those which are critical in some extend for the device or process operation. Examples of such faults and phenomena are bearings faults, misalignment, unbalance, resonance, wear and gear condition. For instance, ISO-standards SFS-ISO-10816 and SFS-ISO-7919 commit on permissible vibration levels in some applications. This subsection introduces fundamentals of a few existing condition monitoring methods. However, this subsection does not introduce specific commercial condition monitoring products. [8] [11] [20]

Condition monitoring systems can be divided in two different categories, which are periodic and permanent measurement systems. In periodic systems, the device or the process is measured at certain time intervals and the sensors can be installed permanently or they can be set in place before each measurement. Measured data can be analyzed at the site or it can be recorded and analyzed elsewhere. This kind of condition monitoring system is usually used when the measured device or process is very complex, or a very early stage fault detection and advanced diagnostics are required. In turn, permanent measurement system is usually online-system that is part of the device or process control system. This kind of condition monitoring is used to generate warnings or it can shut the device or the process down if necessary. Permanent condition monitoring is generally used when the component breakdown causes device shutdown, or it may cause personal injury or environmental accident. [20]

Successful machine condition monitoring and fault detection requires that the characteristics of the device or the process is well-known and the requirements of the condition monitoring system are well-defined. In addition, selecting of the proper condition monitoring method depends on, for example:

- The cost of the device down-time

- The cost of the device itself
- The cost of the condition monitoring system
- Human and environmental safety effects

This enables designing of the appropriate operating condition monitoring system, and selecting the appropriate measurements and data-analysis methods. In following subsections, different condition monitoring methods are presented. [9] [20]

2.2.1 Vibration monitoring

Machine vibration analysis is one of the most used methods in field of condition monitoring, because it is considered as a versatile and accurate method for detecting different kind of faults. The vibration is measured either as a relative or as an absolute value. Relative measurement means, for example, how a shaft vibrates relative to the machine frame [21]. The used sensor types are based on displacement, velocity or acceleration of the measured target as a function of time. Displacement sensors are usually non-contact sensors and the output of the sensor measures relative displacement between rotational and static part of the machine. In turn, the output of velocity sensors can be configured as velocity or displacement, and output of accelerometers can be configured as acceleration, velocity or displacement. Selected sensor type depends on desired vibration frequency range as Table 1 presents. Frequency ranges can differ between different sensor types and manufacturers. [9] [20] [21]

Table 1. *Vibration sensor types. [9]*

Frequency range	Quantity	Phenomenon example
0 Hz to 10 kHz	Displacement	Mechanical clearance, oil-film thickness, incipient rubbing
1 Hz to 2 kHz	Velocity	Mass unbalance, misalignment, looseness
0,1 Hz to 30 kHz	Acceleration	Defects in rolling elements: bearings, gears, pumps, fans

As can be seen in Table 1, the frequency ranges of different sensor types intersect each other. Different phenomena such as shaft misalignment, faulty bearings or gears and too large clearance are examples that cause vibration at different frequencies. Those frequencies depend on the fault type itself, component dimensions and rotational frequency of rotating components. In addition to the frequency range, the sensor is selected according to the measured item and environmental conditions also. This is because different kind of faults appears at different frequency of vibration and, for example, extra low or high temperature or magnetic fields may interfere with some sensors. [11] [12] [20] [22]

Especially in crushing plants, the measured devices vibrate quite strongly even if they are in good condition, so a momentary vibration of a machine does not necessarily tell much about the condition. Instead, vibration based condition monitoring system monitors usually changes in vibration. The measured vibration value is compared to the reference vibration spectra that is measured when the device was certainly in good condition. [9] [20]

The selected data-analysis method depends on the phenomena that is observed. SFS-ISO 13373-1 –standard lists some of the common analysis methods: [9]

- Trending the broadband values
- Frequency spectrum analysis
- Trending discrete-frequency spectral data
- Trending limited-frequency-band or narrow-band frequency spectral data
- Cascade analysis
- Bode, Nyquist or polar plots, vector analysis
- Shaft orbit analysis

Chapter 2.4 presents in more detail the data-analysis methods used in this work.

2.2.2 Temperature monitoring

The temperature of most devices is in certain range, when they are in normal running state. When problems occur, the temperature of the device or part of the device changes outside the normal range. For example, insufficient lubrication, wear and high load may increase the temperature of the related component. Temperature measurement methods can be separated in three categories: thermal imaging, point-form temperature measurement and bulk measurement. [22] [23]

Thermal imaging can be made with infrared (IR) camera. Thermal image reveals the part of the device, which temperature is changing. The benefit of the thermal imaging is that one measuring device can monitor different components and different parts of those components. Online thermography based condition monitoring system is quite expensive to purchase, but it is reliable. Optionally, the measurement can be taken manually and sent to a specialist, who analyses the images. The purchase cost of this option is not so expensive, but the analysis of the thermal images may be expensive. In this case, the interval of the measurements may increase and due to that, the whole potential of the condition monitoring is not utilized. [22]

Point-form temperature measurement is used to measure a certain component temperature such as electric motor windings, or a bearing housing so that the rise in temperature of the bearing itself can be detected. Exceptional measurement value indicates that problem may occur, but specific fault point may be difficult to expose, because the source of the heat may be some other component near the actual monitored component. A clear benefit of the point-form methods is that a single measurement is quite inexpensive to implement, so especially the costs of smaller systems are lower. In turn, some of the temperature sensors needs to be built-in in the component. A failure of a built-in sensor might cause high cost, because the whole component needs to be replaced. Temperature sensor of electric motor winding can be an example of such a case. Furthermore, the need of built-in sensors may reduce possibilities to sell the condition monitoring system to the older machines. [15] [22]

The principle of bulk measurement is to measure, for example, hydraulic oil temperature, radiator fluid temperature or lubrication oil temperature, and detect if the temperature goes outside from the normal operational range. This kind of solution is very low cost, but it does not identify the source of the heat. This kind of technique can be used to detect some general fault. [15]

2.2.3 Shock pulse analysis

Shock pulse analysis is developed especially for rolling element bearings. The method is based on ultrasonic shock pulses that are generated by the mechanical impacts that are caused by bearing damages. For example, if there is a crack in a bearing ball, the mechanical impact occurs when the cracked point of the ball comes into contact with the bearing ring. [22]

The measurement can be made with piezoelectric accelerometer which resonant frequency is tuned around 32 kHz. Shock pulses excite the sensor oscillation at the damped frequency, and the amplitude oscillation and the rate of pulses are measured. The lower frequencies of the measurement signal are filtered so that phenomena, such as imbalance, do not disturb the shock pulse detection. [22]

Detecting the bearing faults is based on monitoring the impact amplitudes at different rates of impacts, and comparing them to the measurement values taken from a bearing that is known to be in good condition. That is necessary, because the surface roughness of the bearing components causes some shock pulses in good bearings as well. Bearing dimensions and speed affects to these shock pulses too. Shock pulse measurement devices measure usually two different shock magnitude values. So called carpet value of the shock pulse magnitude is measured at high rate of shock pulses (over 1000 pulses per second) and the maximum value of the shock pulse magnitude is measured at low rate of impacts (over 25 pulses per second). For instance, if the maximum value stays constant but the carpet value increases, it may indicate lubrication issue. [22]

2.2.4 Oil analysis

In different kind of machines, huge amount of oil is circulated inside the machine. Hydraulic system uses it to transfer power, and lubrication system uses it for lubrication and cooling. The oil circulates through the parts, such as cylinders, gears and bearings, which condition may be interesting to monitor. Despite the good lubrication, the components wear and cause small particles in the oil called wear debris. [22]

Wear debris analysis is based on the finding that different kind of wear causes different kind of wear debris. Magnetic plugs and chip detectors, ferrography, particle counter, spectrograph oil analysis and lubrication oil analysis are examples that can be used to analyze the wear debris or the oil. Most of these methods, however, is not suitable for online condition monitoring and requires expensive laboratory tests. [22]

2.2.5 Acoustic emission monitoring

Acoustic emissions are sound waves that are generated by the material that is under stress. Especially in metals, acoustic emission is emitted by the plastic transformation and cracks. The frequency range of the emission is usually between 50 kHz and 2 MHz. [22]

Failure detection is based on the change in measurement signal. For example, worn gears and poorly lubricated bearing, or bearing lubricated with contaminated lubrication, emit different acoustic signal than gears or bearings in good condition. The signal characteristics that are monitored are usually:

- Measurement signal peak amplitude
- Count, that is, how many times pre-set signal amplitude threshold is exceeded
- Events, which consist of several counts, but they are considered as one event
- Energy of the measurement signal. [15] [22]

The measurements can be made with resonant piezoelectric sensors that measure only the frequencies near the resonant frequency of the sensor or, if the frequency analysis is needed, the broadband measurements are possible too. [22]

The benefits of AE measurements are that, for instance, cracks under the surface can be detected and in some cases, the evolving faults are detected earlier with AE measurement than with vibration measurement. The disadvantages of this condition monitoring method are high sampling rate and complex signal processing that increases the cost of the system, especially if high number of measurement points are needed. [15] [22]

2.2.6 Electrical signal monitoring

Alternating current (AC) motors and generators are widely used in many industries, and usually the whole process depends on their functioning. By monitoring the electrical signal of the motor/generator, such as current, power and flux, it is possible to detect different kind of electrical and mechanical faults. Examples of these are, among others, bearing faults, imbalance, broken rotor bars and rotor asymmetry. [22] [23]

The operational principle of an AC motor can be described in a nutshell as follows. Stator windings are fed with AC power, which generates a rotating magnetic field. The rotor of the motor includes most commonly a permanent magnet, independently excited windings or short-circuited windings. Commonly used induction motor uses short-circuited rotor windings. In induction motor, the rotating magnetic flux generated by the stator, induces current in opposite direction in the rotor windings, which in turn, magnetizes the rotor windings. The stator and rotor magnetic fields are in opposite direction, so the rotor tends to resist the rotating magnetic field of the stator, which produces magnetomotive force that rotates the rotor. In induction motors, because the magnetic flux magnetizes the rotor, the rotor rotates slightly slower that the magnetic field produced by the stator. This rotational speed difference is called *slip*. The other most common used electrical motors are usually synchronous motors, which rotor rotates with same angular velocity than the magnetic field of the stator. [24]

Many of the used analysis methods are based on time domain or frequency domain analysis of different electrical signals. For example, in frequency analysis, the certain faults cause specific kind of magnitude growth of measurement signal at specific frequencies, which can be considered as a kind of a fingerprint. In addition, depending of the fault type, electrical supply frequency, motor pole number and slip are characteristics of the motor among other things that affect how the fingerprint is placed in the frequency domain. [23]

In these days, frequency converters have become more common as a part of electric motor drives. The functioning of frequency converters require different kind of measurements that are useful also in condition monitoring of electric motor, and frequency converter itself. For instance, supply frequency and supply current measurements enable spectrum analysis of stator current that reveals rotor bar failures or mechanical unbalance. In addition, when vibration based condition monitoring is used, the motor should usually be in steady state, so the frequency converter measurements can be used to identify if the motor is in steady state or in transient state. However, the use of frequency converter measurements can also bring challenges. For example, the spectrum analysis of motor stator current can be challenging, because the waveform of the frequency converter is highly distorted. Furthermore, if stator current measurement is used for condition monitoring purposes, it should be made sure that current measurement is implemented as three-phase measurement, not two phase-measurement that assumes the current as symmetric input. In addition, when induction motor is used, it should be remembered also that rotor speed is slower than measured stator input voltage frequency due to slip. [25] [26]

2.2.7 Condition monitoring strategy

The implementation of a condition monitoring system strongly depends on the monitored machine or process, because different processes have their own characteristics. For example, in many processes the load and velocity of the components may be almost constant during normal operation. In turn, in rock crushing equipment, the load of the components changes constantly and the environmental conditions are harsh. The following paragraphs introduce a guideline to follow in CMS implementation.

The first step is to map the requirements of the CMS and decide, whether the system needs to be implemented as online or periodic system, and should the periodic system be installed permanently or temporary. Complexity of the process, desired impact and the expected price of the CMS define the conclusion. [20]

The second step is to list all the devices of the process according to their criticality. The more critical device, the more the failure affects the production or safety. After this listing, the third step is to list characteristics of the machine. For example, in frequency analysis, the monitored frequencies depend on the natural frequencies of the device parts, gear tooth number, rotational speeds and electrical motor pole numbers. They all are characteristics that are needed in data-analysis. [20]

The fourth thing is to define the suitable sensors and measurement parameters. For example, if the temperature based monitoring has evaluated as the best solution, the type of the temperature measurement should be decided. Respectively, if the vibration based monitoring is assessed as the best solution, it should be evaluated based on the measured phenomenon, is the displacement, velocity or acceleration based vibration measurement used. The most suitable vibration sensor type depends on the frequency range at where the phenomena occur, as the Table 1 suggests. [20]

When the sensors are selected, the placement of the sensors need to be obtained. If the temperature and vibration based methods are used as an example again, the temperature sensors need to be located so that temperature of other than the monitored component does not affect the results. In turn, with vibration measurement, SFS-ISO 13373-1 standard gives guidelines how the vibration sensors should be located. [20]

The sixth phase is to define the time interval between measurements. In principle, shorter measurement interval is needed if the potential faults develop quickly or the speed of fault development is not known. In addition, the measurement interval should be decreased, when the first observations of the development of the fault is detected to make sure that the failure does not occur before the next measurement. In turn, the measurements need to be executed so that measurements are comparable to the previous measurement. [20] [9]

The last thing to do is to design and select how the data is collected, stored and analyzed. Data collecting sequence must be implemented so that all relevant data is collected at the same time. For example, in vibration monitoring of rotating devices, the rotational speed needs to be measured, because it is important information in data-analysis [20]. In addition, good planning of the sequence could reduce the price of the CMS. For instance, if Bluetooth low-energy (BLE) sensors are used, the BLE gateway can usually communicate with limited number of sensors at once. BLE gateway could disconnect those sensors, which measurement is not needed constantly, in which case, the gateway capacity can be artificially increased and gather data from more sensors than continuous connection enables.

With data storing and data-analysis, it needs to be assessed at what level the data storing and analysis is the most expedient and effective:

- Is the raw data stored or just some key indicator values?
- Is the data stored at the site or is it sent to a cloud service?

- In which level the data-analysis is performed? Does the sensor perform data processing and analysis, or is the analysis performed in site level computer, or in a cloud service?

The requirements set to the CMS helps to answer the questions above. Storing raw data requires more capacity, but machine failure could be easier to figure out afterwards when raw data is available. In turn, some customers may be skeptical towards cloud services or the data communication can depend on an expensive satellite connection, so the data needs to be stored at the site. This has to be considered within the system also, because for example, sensor level temporary data storing or buffering may be required, if the data link from the sensor is not fast enough compared to the measurement frequency. Such issues have to be considered also with data-analysis. Cloud computing is a cost effective way to analyze the data, but transferring data could be too expensive or it is not allowed by the customer.

2.3 Used sensors

The rise of the internet of things has brought with it a variety of different low-cost multi-sensor platforms (MSP). Therefore, for comparison, two of the measured phenomena in this work are measured with both wired and wireless sensors in parallel. The wireless acceleration measurements are made with Texas Instrument (TI) CC2650 Sensor Tags and the wired acceleration measurements are made with IFM Electronic VSA001 sensors and VSE001 diagnostic electronics. In turn, inclination is measured with Proemion CAN-sense ACC3501 sensors. The sensors and their operational principles are presented in this subsection, but the measurement setup, in turn, is described in section 3.

Measurement methods based on capacitance change can be implemented in a few ways. Capacitance is directly proportional to the area of capacitor electrode and dielectricity of the material that is between the capacitor electrodes, and inversely proportional to the distance between the capacitor electrodes. Thus, the measured phenomenon needs to change the area, distance or dielectricity between the capacitor electrodes. [27]

Figure 2 presents a simplified accelerometer which capacitor electrode of the sensing element moves between two fixed capacitor electrodes. In addition, the dynamics of the sensor is simplified as spring-mass-damping system.

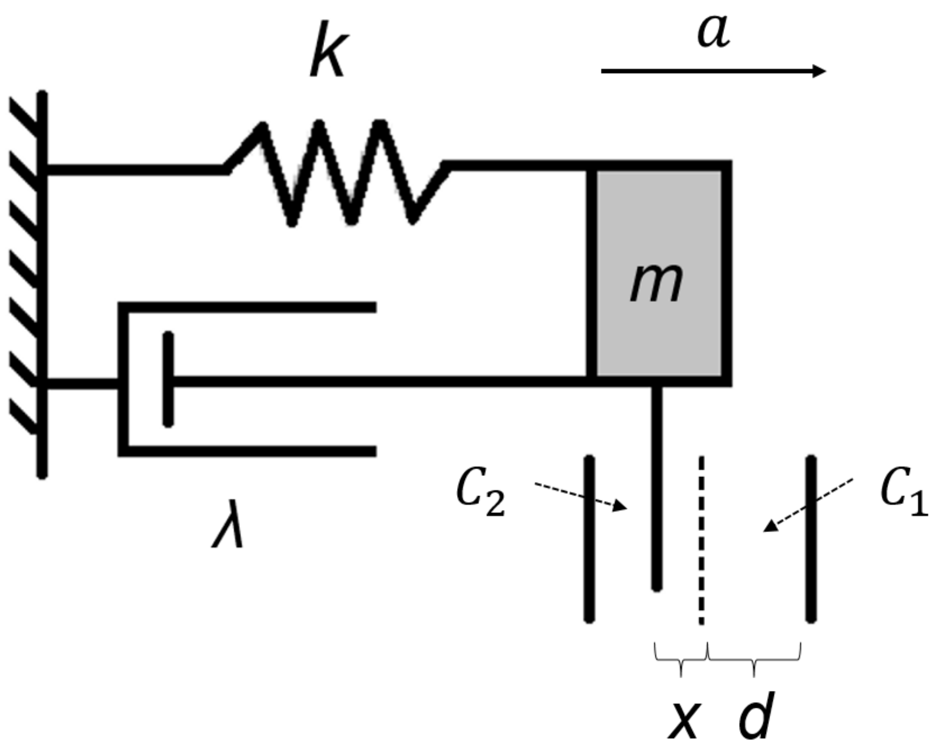

Figure 2. *Spring-mass-damping –system.*

The sensing element of the sensor is a component, which has mass m that is intended to react to the measured phenomenon. The moving sensing element is mounted to the fixed part of the sensor, and the attachment acts as well as spring and damping element. Constant k represents the spring constant of the attachment and λ represents the damping coefficient of the attachment. Differential equation of the spring-mass-damping system dynamics is presented in following equation

$$m\ddot{x} + \lambda\dot{x} + kx = ma, \tag{1}$$

where a is acceleration of sensor casing, $\ddot{x}$ is sensing element acceleration, $\dot{x}$ is sensing element velocity and x is displacement of the sensing element from its rest position. Variable d is distance of sensing element electrode from both fixed electrodes as Figure 2 presents. [27]

The dependence between capacitance and distance between capacitor electrodes are non-linear because of the inverse proportionality. When sensing element is between two fixed electrodes, the sensor consists of two capacitors with different capacitances. The equations of those capacitances are

$$C_1 = \frac{\varepsilon\varepsilon_0 A}{d + x}, \tag{2}$$

$$C_2 = \frac{\varepsilon\varepsilon_0 A}{d - x}, \tag{3}$$

where ε is relative permittivity of dielectric medium, ε_0 is permittivity of vacuum and A is area between capacitor electrodes. The benefit of using this kind of structure is that by using so called deflection bridge connection, the bridge output voltage depends linearly on the variable x. The output voltage of capacitive deflection bridge V_{out} can be calculated as

$$V_{out} = V_s\left(\frac{C_2}{C_1 + C_2} - \frac{1}{2}\right), \tag{4}$$

where V_s is source AC voltage of the bridge. When equations (2) and (3) is substituted to the equation (4), the output voltage of the bridge is

$$V_{out} = \frac{V_s}{2d}x. \text{ [27]} \tag{5}$$

Next, the output voltage can be transformed, for example, to 4-20 mA current signal by using proper amplifier system [27]. When the output signal dependency from displacement x and characteristics of the sensor are known, the acceleration can be calculated by using equation (1). The used dynamic model, how the derivatives of x is calculated and signal processing methods used likely depends on sensor manufacturers.

2.3.1 Texas Instruments Sensor Tag CC2650

Texas Instruments CC2650 is a MSP that uses BLE for data transmission, and includes 10 different sensors [28]:

- Ambient light
- Infrared temperature
- Accelerometer
- Gyroscope
- Magnetometer
- Pressure
- Humidity
- Microphone
- Magnetic sensor

BLE is not a traditional industrial network technology, but almost every mobile devices such mobile phones and tablets are Bluetooth compatible, so it may open new opportunities how the CMS can be implemented and used.

Acceleration values are read from a MPU-9250 multi-chip module which is a combination of 3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer. The Sensor Tag is presented in Figure 3. [29]

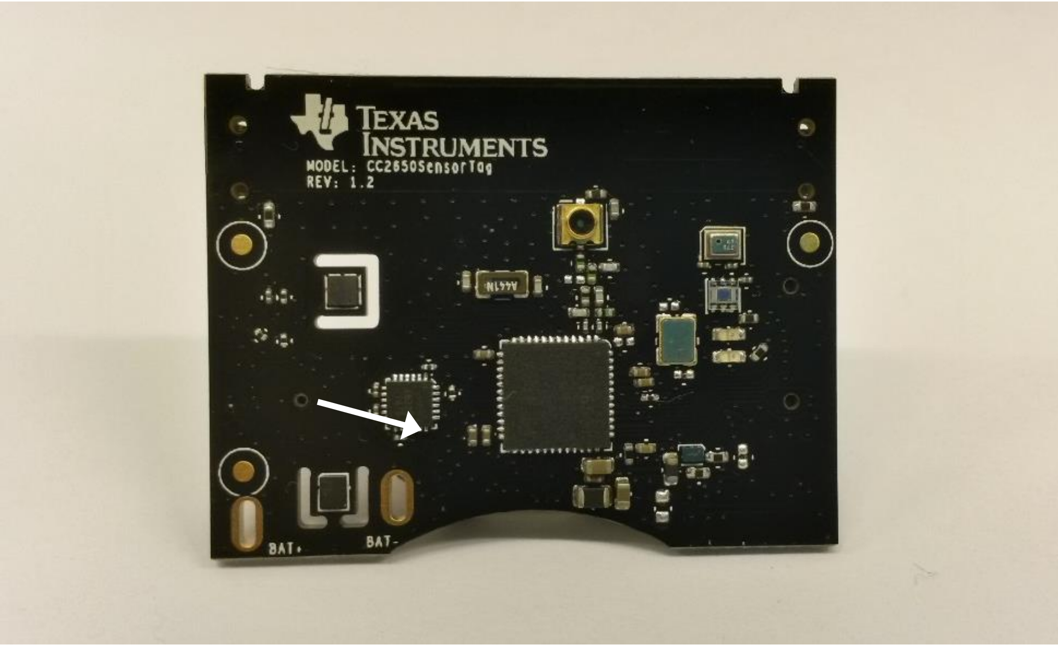

Figure 3. *Texas Instruments CC2650 Sensor Tag. White arrow points to the MPU-9250 sensor.*

The original enclosure and power supply of the Sensor Tag are insufficient for measurements that are performed in this work. Figure 4 presents the improved enclosure solution for the CC2650 Sensor Tag.

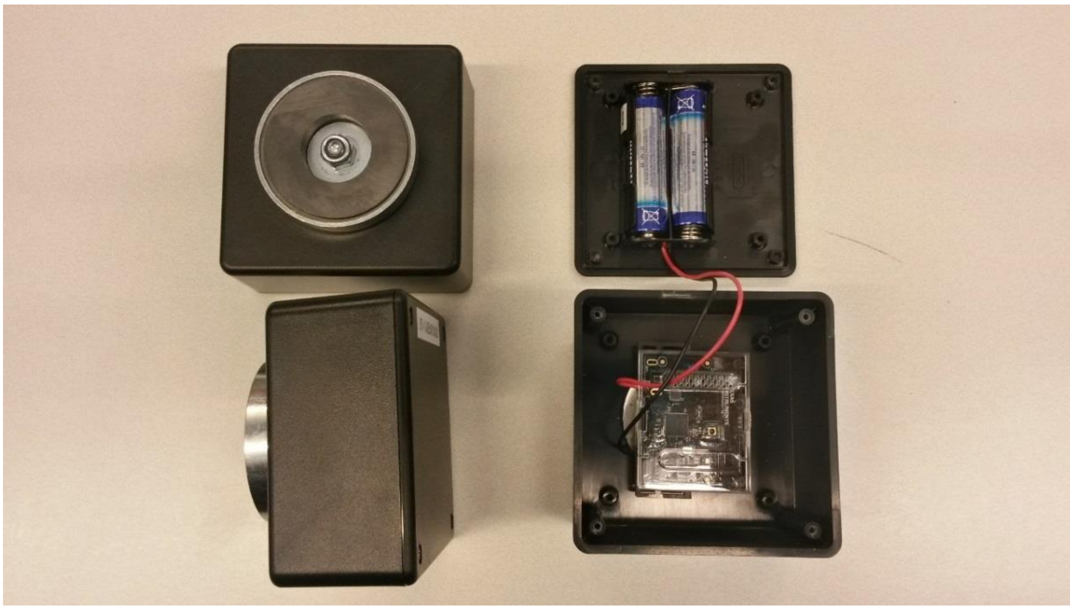

Figure 4. *Enclosure solution for TI Sensor Tag.*

An opened sensor packet is presented in the right side of the Figure 4. The original 3V coin-cell battery is replaced with two AA-sized alkaline batteries, so that the battery is sufficient for higher measurement frequency. The initial maximum measurement frequency is 10 Hz, but it is increased to 100 Hz for this work. The improved enclosure solution consist of extra enclosure that holds the new battery holder and the original holder of TI Sensor Tag. The Sensor Tag holder is attached with hard adhesive to a custom-made thrust journal bolt, which is attached to a mounting magnet. In this way, the amount of damping elements is minimized within the framework of the available resources.

2.3.2 IFM Electronics VSA001

The wired acceleration sensor, IFM Electronic VSA001, is a micro-electro-mechanical system (MEMS) that measures acceleration in a single dimension, and complies capacitive measurement principle. The sensor is presented in Figure 5. [30]

Figure 5. *IFM VSA001 vibration sensor.*

Viewed from Figure 5, measurement direction is from right to left. The sensor can measure vibration up to 6000 Hz. The sensor output is 0-10 mA analog current signal, which is transmitted to VSE001 diagnostic electronics via M12 4-pin connector cable. [30]

2.3.3 Proemion ACC3501

Another wired acceleration sensor used in this work is Proemion ACC3501 sensor. The sensor is connected to a CAN bus with CANopen DS301 protocol. The sensor is presented in Figure 6. [31]

Figure 6. *Proemion CANsense ACC3501 sensor.*

The sensor measures acceleration internally in three dimensions with one millisecond interval, but the minimum interval of sending the measurement values, or measurement window, is 10 milliseconds. The sensor can be configured to send three different measurement values:

- Peak acceleration during measurement window
- Peak acceleration during crash event
- Average acceleration during crash event

Crash event option is not utilized in this work, but it is possible to set a crash event acceleration limit to the sensor. In situation, where the acceleration limit is exceeded at any direction, it is considered as crash event. When the acceleration is not over the crash event limit anymore, the sensor sends process data object messages that includes crash event time in milliseconds and average or peak acceleration for each dimension during crash event. [31]

2.4 Data-analysis methods

This subchapter presents the data-analysis methods used in this work. Generally, the used quantities in vibration monitoring are displacement, velocity and acceleration, and these quantities can be mathematically converted to each other. In this work, the conversion from acceleration to velocity is used so it is presented. Furthermore, vibration frequency spectra, vibration trending, envelope analysis and acceleration based calculation of inclination are presented.

2.4.1 Conversion of vibration from acceleration to velocity

In vibration analysis, the monitored frequency range depends on the monitored phenomena as Table 1 suggests. This is because, for example, low frequency phenomena are easier to detect via displacement, and in turn, high frequency phenomena are easier to detect via acceleration signal. Vibration measurement can be implemented as displacement, velocity or acceleration, and the signal can be converted between these quantities by means of integration and derivation. Integral from acceleration is velocity and integral of velocity is displacement, and conversion works in the opposite direction by using differentiation. [27] [32]

In this work, the conversion from acceleration velocity is used. The exact mathematical relationship between acceleration a and velocity v can be presented as equation

$$v(T) = \int_0^T a(t)dt, \tag{6}$$

where T is the end time of the integral, that is, duration of the signal to be integrated if start time is considered as zero. However, the measured acceleration signal is discrete, so the integral needs to be approximated. Figure 7 presents the idea of the approximation.

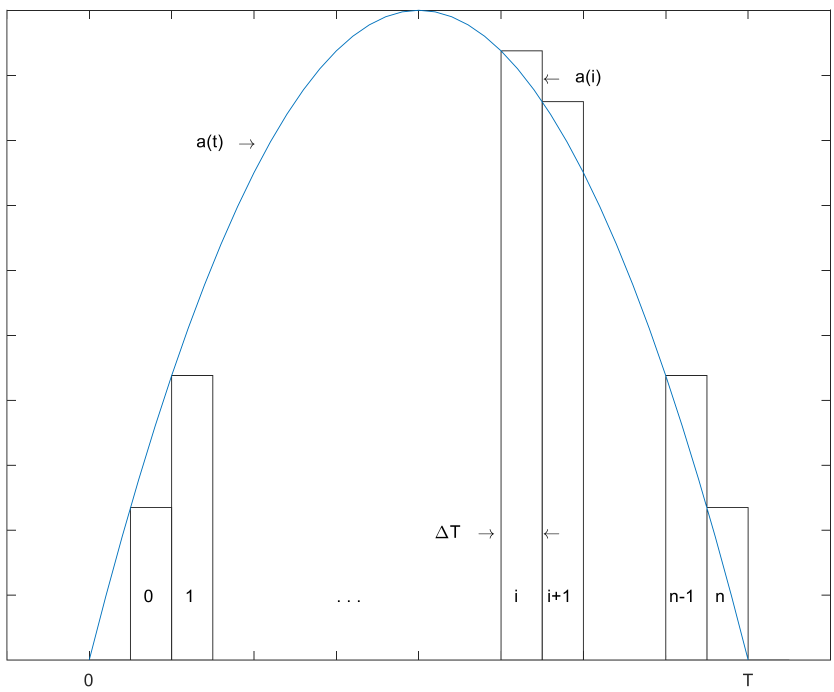

Figure 7. *Explanatory figure of discrete integral. [27]*

When the Figure 7 is put in the form of an equation, the approximation of the conversion from acceleration to velocity is formed as

$$v(T) \approx v[N] = \Delta T \sum_{n=0}^{N} a(n), \tag{7}$$

where the measurement signal, which duration is T, is divided into $N + 1$ parts, and the interval between measurement points are ΔT so that $T = \Delta T(N + 1)$. [27]

Low-frequency signal or frequencies below the interesting frequency range may dominate in integrated signal, which is in this case vibration velocity, so the signal needs to be high-pass filtered before integrating. This is done so that only the interesting frequencies can be monitored. [32]

2.4.2 Vibration frequency spectrum

Many defects related to bearings, shafts and other rotating parts cause certain vibration frequencies. These frequencies depend on, for example, dimensions and rotational speed of the measured component. This subsection presents the transition from time domain to frequency domain and presents what frequencies should be monitored with bearings. [20] [32]

If it desired to view the frequency content of measured vibration, the time domain data needs to be transformed to frequency domain. This can be made by computing discrete Fourier transform (DFT) with fast Fourier transform (FFT) algorithm from discrete measurement signal. Vector of frequency-based data y can be presented as follows

$$X[p] = T \sum_{n=0}^{N-1} e^{-j*2*\pi*p*n*T} * x[n], \tag{8}$$

where x is the time-based data vector at where the sampling interval are assumed to be constant, N is the length of vector x, i is imaginary unit, and both p and n are indexes that runs from 0 to $N - 1$. [33] [34] [35] [36]

With several evolving faults, the dominating frequency, at where the amplitude of vibration increases in vibration spectrum, is the same than the rotational speed or multiple of the rotational speed of the machine. Depending of the fault, the increased vibration can be detected in radial and/or axial direction. Exceptions for the faults that can be detected at the rotational speed or above are, for example, loose housing of a journal bearing, in which case, the domination frequency is 42-48% of the rotational speed. The second example is oil-film whirl or whip in journal bearing, which in turn, appears at ½ or ⅓ from the rotational speed. [20] [32]

In this work, the monitored bearing is a rolling element bearing. Rolling element bearing consist of outer and inner races, rolling elements and cage as Figure 8 presents.

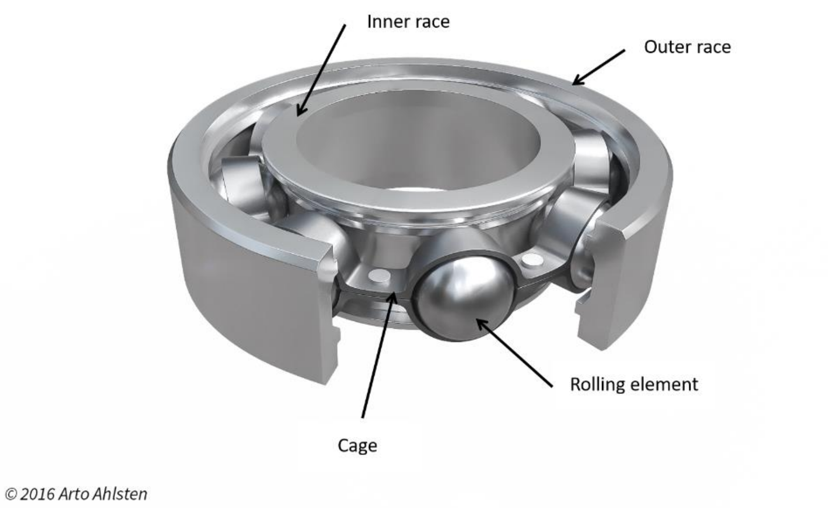

Figure 8. *Rolling element bearing with single rolling element row.*

Different components move in different way in relation to each other. Because of this, the dominating frequency, that amplitude growth reveals the fault, differs from each other. The dominating frequency of single fault related to the outer race of the bearing can be calculated as follows

$$f_{BPFO}(Hz) = \frac{n_b}{2} f_r \left(1 - \frac{BD}{PD} cos\beta\right), \tag{9}$$

where n_b is the number of rollers, f_r is relative rotational speed between inner and outer races of the bearing, BD is roller or ball diameter, PD is pitch diameter of the bearing and β is the contact angle between roller and race. In turn, the dominating frequency of single fault related to the inner race of the bearing can be calculated as follows

$$f_{BPFI}(Hz) = \frac{n_b}{2} f_r \left(1 + \frac{BD}{PD} cos\beta\right), \tag{10}$$

and the dominating frequency of single fault related to a ball or roller defect of the bearing can be calculated as follows

$$f_{REDF}(Hz) = \frac{PD}{BD} f_r \left[1 - \left(\frac{BD}{PD} cos\beta\right)^2\right]. \tag{11}$$

Because the fault in rolling element causes impact when the fault area hits both inner and outer races, the rotational frequency of rolling element is $f_{RFR}(Hz) = \frac{1}{2} f_{REDF}(Hz)$. The last basic fault type is bearing cage unbalance, which fault frequency can be calculated as follows

$$f_{FTF}(Hz) = f_r\left(1 + \frac{BD}{PD}cos\beta\right). \tag{12}$$

ISO-standard SFS-ISO 13373-3 Appendix D gives more information from different kind of faults that can be monitored from vibration acceleration signal. [20] [37] [38]

2.4.3 Vibration trending

The idea of the vibration trending is to measure vibration with certain intervals and evaluate when the monitored device needs service. In addition to the vibration level, it is important to identify the rate of change of the vibration, as well as significant deviations. Vibration trending can be implemented as broadband trending, narrowband trending or single frequency trending. Trending can be also used to trend measurement values that are calculated with other data-analysis methods. The monitored frequency band should be selected so that all interesting frequencies are covered. [9] [20]

The interval between measurements should be defined in condition monitoring strategy that is presented in section 2.2.7. Among other things, the criticality of the device and the fault history affect the interval between measurements. Furthermore, the interval is not usually fixed, but often the interval is decreased when increase in vibration level is detected. This enables more precisely prediction when the failure will occur, and on the other hand, the possibility of failure before the next measurement is decreased. [9]

The measured quantity is usually root-mean-square (RMS) value of vibration velocity, because it describes the severity of the vibration in many cases at reasonably wide frequency range. The RMS value of the vibration velocity v_{rms} can be calculated as follows

$$v_{rms} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}|v[n]|^2}, \tag{13}$$

where $v[n]$ is discrete measurement signal of vibration velocity, N is the number of samples in measurement and n is index that runs from 1 to N. [9] [27]

The acceptable vibration level depends on the monitored machine. ISO-standards SFS-ISO-13373 and SFS-ISO-10816 suggest vibration evaluation criteria that are divided in four different zones and general limits for those zones for different machines:

- Zone A: Device in good condition, that is, the device is new or newly serviced.

- Zone B: The vibration level is increased, but it is acceptable even in long term use.
- Zone C: The vibration level is increased, so that long-term use is not acceptable and risk of failure is increased.
- Zone D: The vibration in this level is considered to cause damage to the device.

By dividing the evaluation criteria in different zones, the actions based on present and predicted vibration levels can be performed. When the limits of the zones are defined, the limits are not necessary the same for whole frequency range. If the same limits for vibration velocity are used, the limits may allow excessive large displacement with low-frequency vibration. Especially when the monitored speed is low and the dominating frequency of vibration spectra is same as the speed of the machine. In turn, the limits may allow excessive high acceleration with high-frequency vibration. This is a problem with high-speed machines. [9]

The weakness of broadband vibration monitoring with only one indicator value is that if the monitored frequency range includes some dominating frequencies, the changes in amplitudes of other frequencies do not significantly affect the indicator value. Furthermore, the above-mentioned type of monitoring does not identify the actual fault, and on the other hand, some of the faults may be undetected. In these cases, the trending can be used for single or narrow-band frequency vibration trending. [9] [20]

2.4.4 Envelope analysis

Envelope analysis of vibration measurement is an effective condition monitoring method for rolling element bearings due to its ability to early stage failure detection and its high signal to noise ratio. Measurement signal is usually dominated by low-frequency vibration that can be due to, for example, misalignment, unbalance or it can include some kind of background vibration. In turn, rolling element bearing fault such as crack on the rolling element causes repetitive impacts. These impacts affect the measurement signal so little that they cannot be detected from vibration spectrum, but they excite the natural frequencies of bearing housing. These impacts can be equated with repetitive hitting of tonometer. Each hit excites the natural frequency of the tonometer as the crack on bearing ball excites the natural frequency of the bearing housing. These natural frequencies are amplitude modulated to the hitting frequency. In the case of bearings, the frequencies of the impacts correspond the bearing fault frequencies that are presented in subsection 2.4.2. In other words, the frequency content of these repetitive impacts due to bearing defect is not interesting, but the interesting part is the intensity of the impacts and how often they occur. Because these impacts excite the natural frequencies of the bearing housing, the frequency content around the bearing housing natural frequency is monitored. [20] [32] [39]

Envelope analysis consists basically of three different phases:

- Bandpass-filtering of the raw data

- Envelope detection from the bandpass-filtered data
- Frequency spectrum of the envelope

Figure 9 presents visually how the envelope analysis is performed.

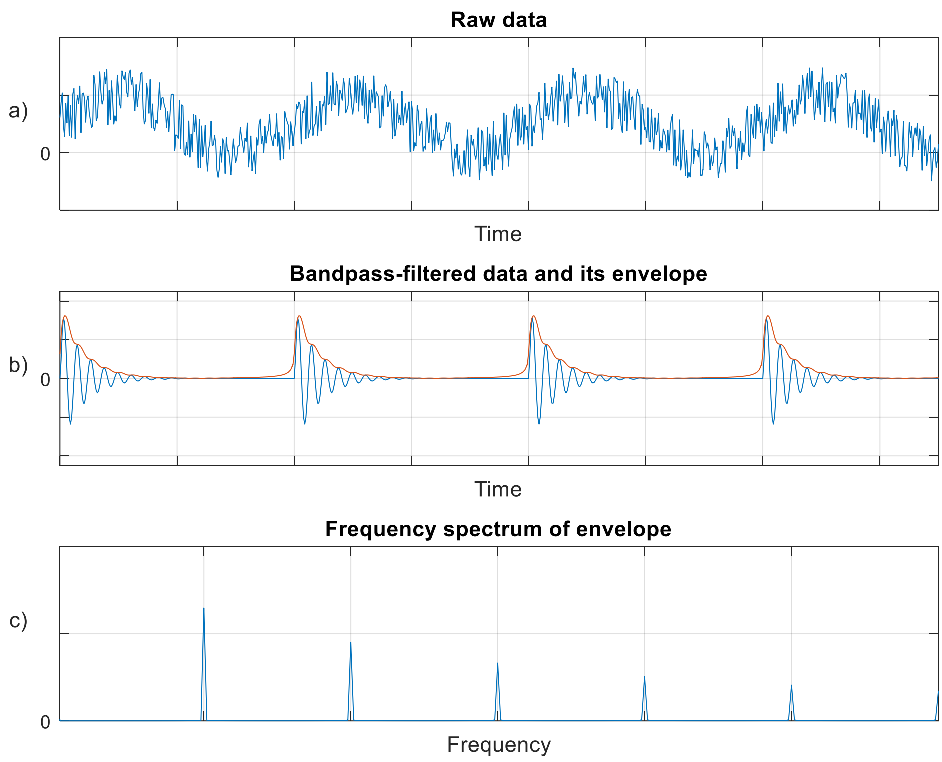

Figure 9. *Principle of envelope analysis: a) Raw measurement from housing of rolling element bearing, b) Bandpass-filtered measurement signal and its envelope, c) frequency spectrum of envelope.*

In Figure 9, the first plot represents raw measurement signal, where low-frequency vibration dominates, but there are also summed high-frequency vibrations due to repetitive impacts and noise in the signal. The first phase of the envelope analysis is to bandpass-filter the interesting high-frequency content around the natural frequencies of bearing housing. The selection of pass band limits can be made in several ways. The first way is to select the limit according to the generally applicable limits given in literature. Table 2 present one suggestion that are used in SKF Condition Monitoring Microlog.

Table 2. *Bandpass-filter range selection according to the machine running speed [40].*

Machine speed	***Bandpass-filter range***	***Analyzing range***
0-50 RPM	*5-100 Hz*	*0-10 Hz*
25-500 RPM	*50-1000 Hz*	*0-100 Hz*
250-5000 RPM	*500-10000 Hz*	*0-1000 Hz*
2500-… RPM	*5000-40000 Hz*	*0-10000 Hz*

The second option is to estimate the natural frequency from the frequency spectrum of the measurement data, if there is a notable rise in amplitudes at higher frequencies. The estimation can be made from actual measurement data, which is used for envelope analysis, or from the measurement data that is collected from so called hammer test. In hammer test, the bearing housing is tapped while the machine is shut down and the natural frequency is estimated from the high-frequency content of the measurement signal. In addition to these methods, there are different kind of methods, such as spectral kurtosis, that aims to optimize the passband in relation to, for example, failure detection or computing power demand. [20] [40] [41]

As Figure 9 presents, the second phase in envelope analysis is to detect the envelope of the bandpass-filtered data. In this work, the envelope is detected with discrete analytic signal of the bandpass-filtered data, which uses Hilbert transform for signal demodulation. The discrete analytic signal for discrete-time signal $x[n]$ is defined as follows

$$z[n] = z_{re}[n] + i * z_{im}[n], \tag{14}$$

where i is is imaginary unit, $z_{im}[n]$ is Hilbert transform of $x[n]$ and $z_{re}[n] = x[n]$ for $0 \leq n \leq N - 1$. In order that $z[n]$ would be an analytic signal, its real part needs to be exactly as the original signal. In addition, the real and imaginary parts of z[n] needs to be orthogonal for $0 \leq n \leq N - 1$ as follows

$$T \sum_{n=0}^{N-1} z_{re}[n] * z_{im}[n] = 0, \tag{15}$$

where T is time interval of signal period. [36]

Before the analytic signal can be calculated, N-point discrete Fourier transform $X[p]$ of original discrete signal $x[n]$ and N-point analytic signal transform $Z[p]$ needs to be calculated. The DFT can be calculated by using equation (8) and the analytic signal transform can be calculated as follows

$$Z[p] = \begin{cases} X[0], & for\ p = 0 \\ 2X[p], & for\ 1 \leq p \leq \frac{N}{2} - 1 \\ X\left[\frac{N}{2}\right], & for\ p = \frac{N}{2} \\ 0, & for\ \frac{N}{2} + 1 \leq p \leq N - 1 \end{cases} \tag{16}$$

where p is used as index. Now the analytic signal can be calculated as follows by using N-point inverse DFT

$$z[n] = \frac{1}{NT} \sum_{p=0}^{N-1} Z[p] * e^{i*2*\pi*p*n/N}. \tag{17}$$

The desired actual envelope is the amplitude vector of the analytic signal $z[n]$, which is the absolute value of the signal as follows

$$x_{envelope}[n] = |z[n]| = \sqrt{(z_{re}[n])^2 + (z_{im}[n])^2}. \tag{18}$$

The frequency spectrum of the envelope can be formed according to the subsection 2.4.2.

2.4.5 Acceleration based inclination measurement

Orientation of a Lokotrack is generally checked before the process is started, and this method is suitable for this purpose. When the process is not running, the dominating acceleration component is caused by gravity.

Inclination should be measured from at least two points, so that the orientation of the Lokotrack can be detected appropriately. The surface on a site is usually really rough, but it is usually smoothed out so that Lokotrack is positioned on a horizontal level. However, the steel structures are always elastic elements, so the frame can be twisted even one-point measurement indicates that the frame is in horizontal level. When two-point measurement is used, the twist can be detected from a difference of two measurement signals that indicate the inclination in same direction.

Depending on the machine and sensor orientation, and when the gravity is the dominating acceleration, the gravity is divided into three different measurement axis of the sensor as can be seen from Figure 10.

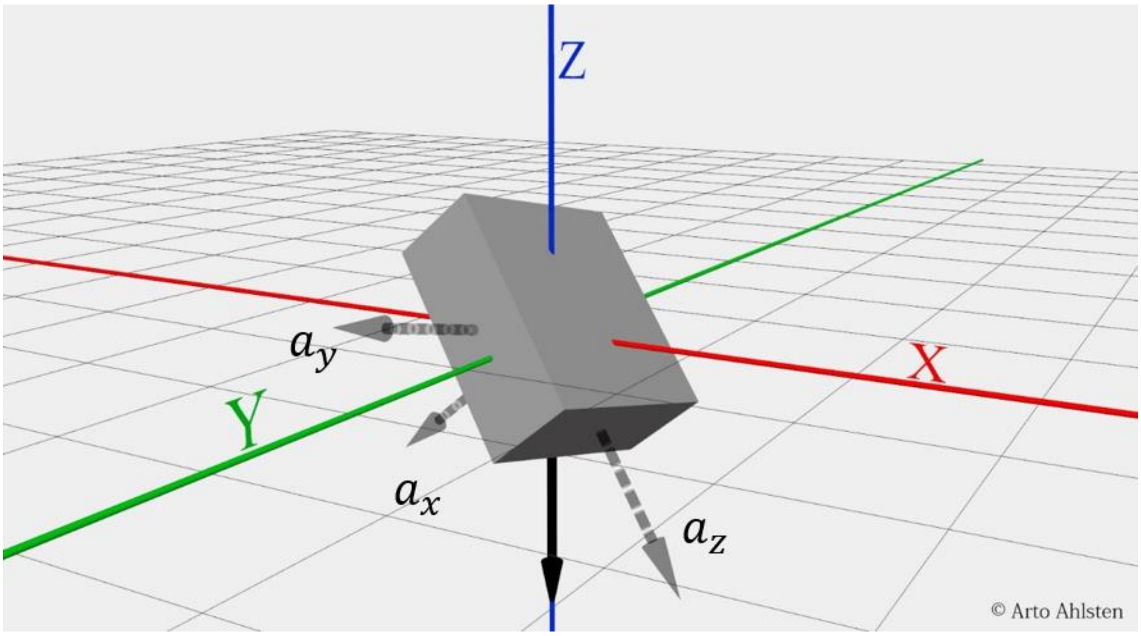

Figure 10. *Principle of accelerometer based inclinometer.*

When the sensor is located in xyz-plane, as in Figure 10, and the xy-plane is considered as flat surface of a ground, the inclination with respect to the y-axis θ_y and the inclination with respect to the x-axis θ_x can be calculated as follows

$$\theta_y = \tan^{-1}\left(\frac{a_y}{a_z}\right), \tag{19}$$

$$\theta_x = \tan^{-1}\left(\frac{a_x}{a_z}\right), \tag{20}$$

where a_x, a_y and a_z are measured accelerations. The variable subscripts indicate the sensor measurement axis. [42]

If it is desired to monitor the orientation of the machine when the process is running, it could be implemented, for example, as Kalman filter based solution, in which the orientation is detected with gyroscope and the acceleration measurement is used for vibration compensation. Vibration compensation is required, because, for example, dumping the motorcycle-sized rocks in the feeder and the crushing of the rocks cause vibration that may disturb the orientation detection. [18]

3. MEASUREMENT SETUP AND EXPERIMENT

This section explains how the potential condition monitoring measurements are selected according to the stage-gate model. In addition, the measurement setup and experiment of this work are described. The description of measurement setup includes used sensor types together with installation locations and methods. Data processing is presented in more detail also.

3.1 Selection criteria of measurement

The scope of this work in state-gate model is to study technical feasibility at stages 1 and 2. A departure assumption of this work has been that actual condition monitoring systems have not been applied in Metso mineral or aggregate processing equipment before. The criteria need to take into account that condition monitoring systems have been developed for more general objects such bearings and shafts before, but there are lack of application specific CMS applications. However, it could be necessary to estimate what are the costs of developing features that monitors these general components also, or is it more profitable to use third party systems to monitor bearings, shafts and so on. Table 3 presents the *have to meet* and *should meet* criteria for gates 1 and 2 in new product development model that is presented in chapter 2.1.

Table 3. *State-gate –model criteria for early gates.*

Criteria
Have to meet:
• Reasonable cost in relation to the price of the machine • Clear benefits • Potential help to find the root causes of failures • Potential tool for detecting evolving faults
Should meet:
• Wireless sensors • Predicts failures that cause warranty costs • Possibility to install as a retro-fit • Does not overlap with condition monitoring systems on the market that could be integrated into the Metso system with reasonable cost

Have to meet criteria give the main guideline how to select the measured devices so that CMS is profitable. The price of the CMS cannot be too high in relation to the price of the machine and the benefits needs to be obvious so that the system is tempting from customer point of view. Attractiveness and utility will increase the earlier the evolving faults can be detected, because then the predictability is realized. In addition, the measurement system is excepted to help finding the root causes of the faults. For example, a root cause may be that Lokotrack is set to rough surface so that the frame of the machine is twisted.

In such situation, in C-jaw crusher, the crusher may be also slightly twisted, so the forces in the crusher differs from the designed.

In this case, *should meet* criteria give more details than *have to meet* criteria. Wireless sensor technology has become cheaper, so the CMS may be more cost effective to purchase, especially as a retro-fit, if the cabling is not required. In addition, one good approach is to pay attention also to the possible faults that are under warranty. In this manner, the faults can be repaired so that the disruption to the customer is minimized. The last *should meet* criterion is related to the fact that the whole system may not be necessary to be developed fully in Metso, because buying some features of the system from third party may be more cost-effective than develop those features in Metso.

3.2 Measurement setup

The machine used in this experiment is Metso Lokotrack LT106. It is a mobile C-jaw crushing unit that is usually used as a primary unit that crushes the quarry rocks [43]. LT106 is presented in Figure 11.

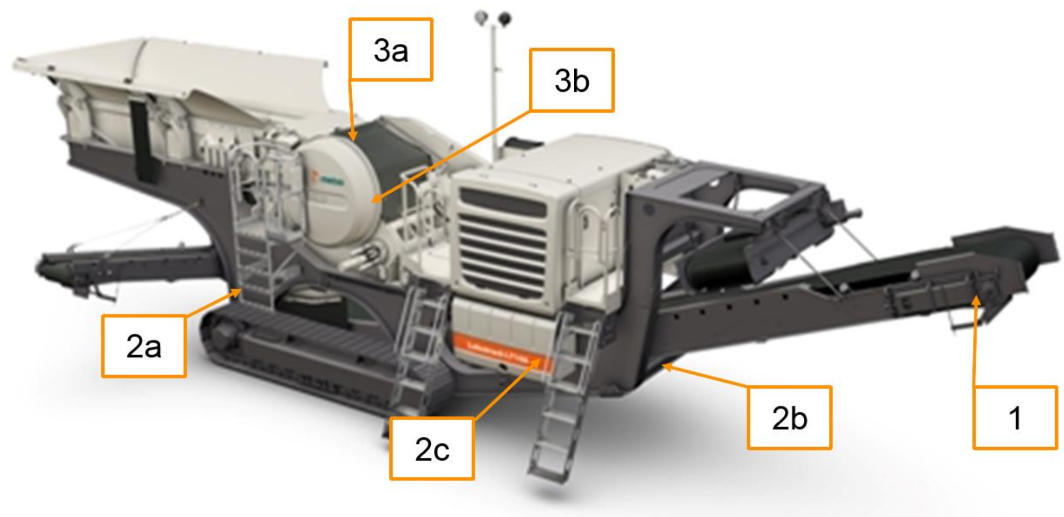

Figure 11. *LT106 and location of measurement points: 1) Conveyor frame, 2a) Feeder side measurement point of the Lokotrack, 2b) Main conveyor side measurement of the Lokotrack frame, 2c) spirit levels, 3a) Vertical vibration measurement of crusher frame bearing, 3b) Horizontal vibration measurement of the crusher frame bearing.*

Measurement setup consists of three different measurement targets, which installation points are presented in Figure 11: Orientation of the Lokotrack frame, swinging of the main conveyor frame and frame bearing vibration of the C-jaw crusher. Each measurement is explained in more detail in following subsections.

The used measurement and network devices are presented in Table 4.

Table 4. *Measuring and network devices and their quantities used in this work.*

Component	**Quantity**
TI Sensor Tag CC2650 rev. 1.2/1.3 **[28]**	3
Proemion CANsense ACC3501 **[44]**	2
IFM electronics VSA001 **[30]**	3
IFM electronics VSE001 **[45]**	1
Raspberry PI 3 Model B V1.2 **[46]**	1
Secomea Sitemanager 1139 **[47]**	1
Moxa EDS-P206A-4PoE **[48]**	1
Wapice WRM247+ **[49]**	1

The measurement system includes sensors and network devices so that the measurements can be made remotely. Figure 12 outlines how the devices of Table 4 is connected to each other.

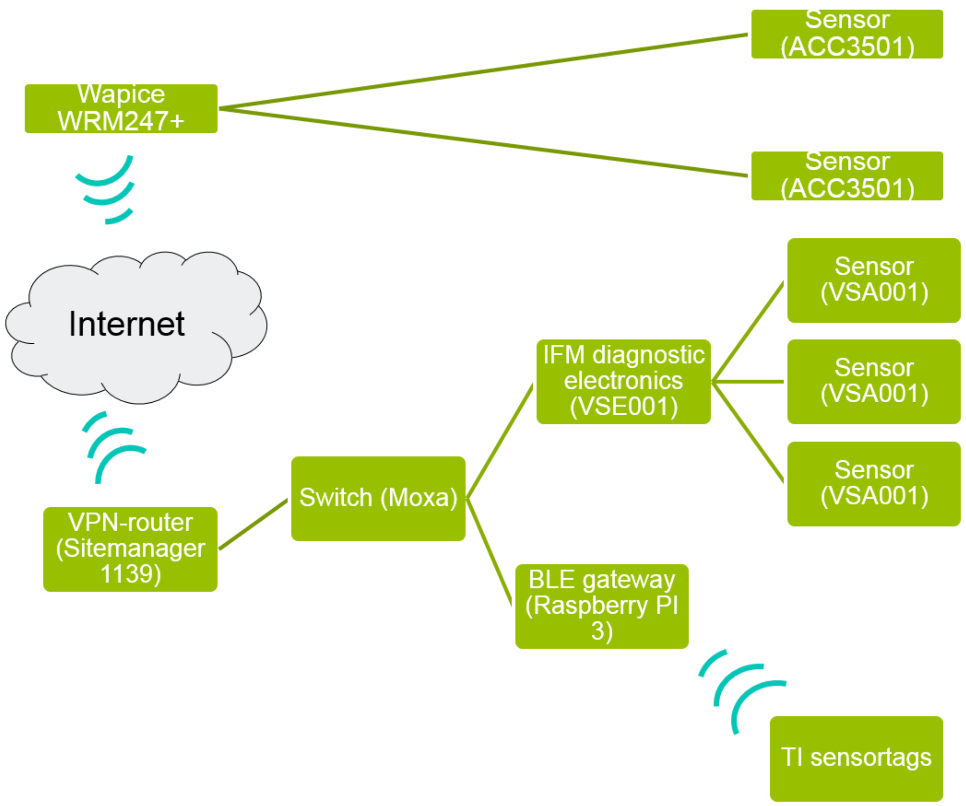

Figure 12. *Outline of the measurement system network.*

First of all, Wapice WRM247+ gathers data from CANsense ACC3501 sensors and transfers the data to my.iot-ticket.com cloud service [50]. In turn, IFM VSA001 acceleration sensors are connected to IFM VSE001 diagnostic electronics, which is connected, together with Raspberry PI 3, to Moxa EDS-P206A-4PoE switch. The switch is connected to Secomea SiteManager 1139 Virtual Private Network (VPN) router. Raspberry PI is used as a BLE gateway for TI Sensor Tags. Except for the sensors, the measurement system is placed in the enclosure, which is located in the control cabin of the Lokotrack as can be seen in figure Figure 13.

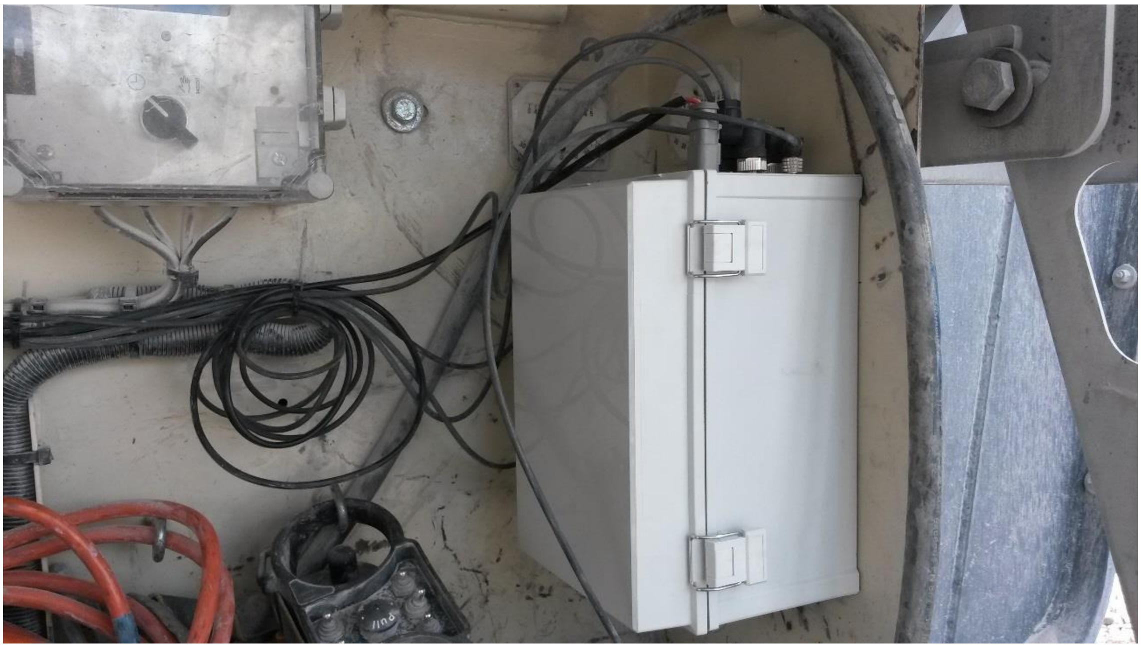

Figure 13. *Measurement box.*

The used enclosure is IP65 rated and the wired sensors are connected to the measurement box with connector instead of leading-through of the wires to make sure that the devices are protected against dust and water.

3.2.1 Conveyor frame

The used conveyor in this measurement is the main conveyor of Lokotrack LT106. Currently, the conveyors visibly vibrate and swing periodically. This phenomenon is measured from the conveyor, because the swinging will speed up the emergence of the failures caused by fatigue, and in addition, swinging consumes energy. Cases in which the conveyor frame has been damaged, the frame has been in resonance before the failure. Based on the criteria in Table 3, the measurement application is somewhat application specific, long-term measurements may be used to identify root causes of the failures, and the measurements can be used to prevent or predict failures. Potential future applications are listed in section 6.

Two different accelerometers are installed to the main conveyor. The wired sensor is IFM VSA001 sensor and the wireless sensor is TI Sensor Tag CC2650. Installation point can be seen in Figure 14.

Figure 14. *Sensors on main conveyor frame.*

The sensors are mounted as near the end of the conveyor as possible. The measuring direction is in such a way that the measurement is perpendicular to the surface of the conveyor belt and the conveyor length direction.

3.2.2 Lokotrack frame

The current method to detect Lokotrack orientation is to use two spirit levels that are located in the control cabinet. The location of the spirit levels is shown in Figure 11. The Lokotrack is allowed to be inclined one degree in lateral[1] direction and two degrees in longitudinal[2] direction. The user is responsible to check the inclination of the Lokotrack, but it is possible that, due to the roughness of the base, the frame can be twisted even the spirit levels at control cabinet is flat. When the frame is twisted, the crusher frame will be also twisted. In that situation, during the crushing process, the resultant force in crusher will differ from the designed. This may cause premature fatigue, wear of the crusher and increase the energy consumption per tonne produced. If the former situation is mirrored to the criteria in Table 3, this measurement not only help finding the root causes and fault detection, but it can be used to prevent faults and misuse of the machine.

The sensors are located at the opposite corners of the frame on feeder side of the machine and on the main conveyor side of the machine, so that the twist can be detected. Both measurement points includes initially both wired and wireless sensors. The wired sensors

[1] Lateral direction is defined as a direction that is perpendicular to the tracks. Positive value of lateral inclination occurs when the track closer to the viewer in Figure 11 is higher than the other.
[2] Longitudinal direction is defined as a direction that is parallel to the tracks. Positive value of longitudinal inclination occurs when the feeder end of the tracks is higher than the main conveyor side.

are CANsense ACC3501 sensors and the wireless sensors are TI Sensor Tag CC2650 sensors. Sensor installation of the main conveyor side is presented in Figure 15.

Figure 15. *Sensors main conveyor side of the LT frame.*

The wireless and wired sensors are installed next to each other so that the measurement results can be compared. The feeder side of the installation is implemented with the same principle than in the main conveyor side as can be seen in Figure 16.

Figure 16. *Sensors in feeder side of the LT frame.*

A noteworthy thing in Figure 15 and Figure 16 is that the sensors need to work under hard conditions: the sensors are affected by weather conditions, and in addition, the process produces rock dust that accumulates over the sensors.

3.2.3 Crusher frame bearing

The Lokotrack used in these measurements is equipped with Metso C106 C-jaw crusher. There are four spherical roller bearing on the eccentric shaft. Both ends of the shaft includes a bearing installed on the crusher frame and on the moving jaw. Currently, the temperature of each bearing is measured by crusher automation system.

The crusher frame bearing is chosen, because it is an expensive and wearing component. On the other hand, it serves an example of bearing monitoring. Furthermore, replacing of a broken frame or movable jaw pitman bearing, that can be seized for instance, is difficult and time consuming. The crusher bearing faults are not common, but when the failure occurs, the shutdown may be relatively long if the failure is unexpected.

Based on preceding and the criteria in Table 3, the monitoring of a bearing gives clear benefit. With right monitoring method, the bearing faults is not unexpected, because development of the failure can be monitored. Bearing monitoring can also prevent the emergence of warranty costs, if the monitoring system can detect premature bearing faults or installation errors. There are plenty of bearing condition monitoring products on the market, but this part of the experiment is indented to help to assess whether the bearing condition monitoring system is worthwhile to develop in Metso or is the use of some ready commercial product the better way.

The crusher frame bearing vibration is measured with two IFM VSA001 accelerometers. Installation of the sensors can be seen in Figure 17.

Figure 17. *Sensors on frame bearing housing.*

In Figure 17, the first sensor measures vertical acceleration and the second sensor measures horizontal acceleration. Temporary mounting of the sensors are made with magnets. It may not be proper solution for long-term installation due to high vibration level of the crusher while process is running.

3.3 Experiment

Experiments performed in this work are presented in this subsection. Each of the measurement target related experiments are individually presented. In addition, used data modifications are also described and justified for each experiment.

3.3.1 Conveyor frame

The wired vibration measurement of conveyor frame is implemented with one IFM VSA001 single axis accelerometer. The location of the sensor is shown in Figure 14. The accelerometer is connected to VSE001 diagnostic electronics, and by using Secomea SiteManager, the measurement signal is recorded with IFM VibrationMonitor VES004 V1.11.04.6786. The diagnostic features of VES004 such as frequency spectrum view are not utilized, but the vibration data is exported in csv format and the data is processed with Matlab R2015b.

The experiment was performed while the process is running. The duration of the experiment was 1 min 14 seconds and the used measurement frequency was 20 kHz, which is the minimum sampling rate of the VES004. The acceleration data was converted to velocity. The velocity data was filtered with bandpass filter so that only the frequency band, in which the conveyor natural frequency can be located, is covered. The natural frequency depends on, for example, the mass of the rock material on the conveyor belt. In this case, the monitored frequency band is 150-280 RPM (2,5-4,67 Hz).

3.3.2 Lokotrack frame

The wired measurement system is implemented with Proemion ACC3501 acceleration sensors, which measure continuously and send the acceleration values of three axes via CAN bus to the Wapice WRM247+, which in turn, sends the measurement data to Wapice iot-ticket cloud service. The Lokotrack is moved when necessary, usually every few days. Therefore, the analysed data is selected in such a way that 16 consecutive working days have one dataset per day. Each data set is picked so that process is not running so that the vibrations caused by the process do not interfere the measurements. The datasets are exported from Wapice iot-ticket cloud service in csv-format, and each data set consists of 100000 data points per measured axis, which means around 16 minutes tracking per axis. Because there were no limitations in amount of data transfer, the length of exported data set is the maximum length that can be exported from the cloud service. Exporting the maximum length data set is the most straightforward way to export data from different days. The data-analysis part is executed with Matlab R2015b, and the analysed data is limited to 5000 data points.

Suitable data modification methods were selected by evaluating measurement data. Zero frequency component of the measurement signal is the most interesting component of the signal, because it is caused by the gravity, and it can be used to calculate the orientation of the sensor relative to the ground. If zero frequency component of the signal is considered as signal and rest of the signal as noise, the signal to noise ratio reveals that the zero component of the measurement signal is really dominating. The signal to noise ratio were around 20-30 dB in pre-experiment data. In this case, the mean value of the measurement signal can be used in orientation calculations.

The reception of the BLE sensors caused problems during the experiment. During pre-experiment, the reception of the BLE sensors located to the Lokotrack frame were tolerable. However, during the first measurements of the experiment the use of them discontinued.

3.3.3 Crusher frame bearing

The frame bearing measurements are implemented with two IFM VSA001 accelerometers. The measurement event uses the same hardware and monitoring software that is used with main conveyor related measurements in subsection 3.2.1. That is, the measured raw data is recorded with IFM VibrationMonitor VES004 and the data is exported in csv format so that data can be processed with Matlab.

Due to the limitations of VSE001 diagnostic electronics, the measurement was performed one measurement channel at a time. The measurements were carried out so that the crusher runs around normal operating speed and the crusher is not fed. This is made, so that crushing of the rocks and load variations cannot interfere the measurement event. In addition, the situation described above is easy to repeat and execute comparative measurements.

The experiment was carried out with 20 kHz measurement frequency. The recorded data set included 424800 data points in vertical direction (around 21,24 seconds) and 477600 data points in horizontal direction (around 23,88 seconds). Different data-analysis methods require different kind of pre-processing of the data, so the only common pre-processing were trend removing from the signals.

4. RESULTS

The results of this work are presented in this section. The first subsection introduces the main phases and lessons learned concerning of the measurement system development. The second, third and fourth focus on the results that have been obtained by using the wired measurements. The last subchapter compares the technical and financial features of the sensors, which compares the functionality of wired and wireless sensors in the site environment also.

4.1 Development of the measurement system

Development of the measurement system consists of selecting and purchasing the suitable measurement instruments and network equipment. In addition, some of the devices needed structural modifications and modifications in software as well. This subsection describes the substance of the measurement setup development.

The first thing was lack of BLE gateway for TI Sensor Tags. There was no suitable BLE gateway for this purpose on the market, but considering the scope of this work, the proper sophisticated gateway solution proved to be too time-consuming. Eventually, the minimum viable version of the BLE gateway was implemented with Raspberry Pi 3 (operating system: NOOBS Version 1.9.2) and Node-RED. Node-RED is flow-based programming tool for Internet of Things, which uses Node.js platform. Before each measurement event, the Node-RED flow is started and the measurement data is collected to USB-drive that is connected to the Raspberry PI. The data can be transferred remotely from the USB-drive via File Transfer Protocol (FTP) over the internet.

The implementation of increased sampling frequency of the TI Sensor Tags required getting familiar with the sensor software code. The used development environment is Code Composer Studio Version 6.1.3.00034 and Code Composer Studio Cloud IDE Version 1.6.0. The final solution is basically the CC2650 example project, except the MPU-9250 measurement interval is shortened and the measurement value is sent with 10 ms interval. During the first sensor tests with a Lokotrack, it was found that heavy steel structures really interfere the reception of the BLE signal. In addition, signal reflection from structures of the machine and from other machines causes diversity to the reception. Due to the lack of data buffering of the sensor, the realized measurement rate is non-uniform.

The wired measurements were easier to implement. IFM sensors and diagnostic electronics needed just installation and getting familiar with diagnostic software. Proemion ACC3501 CAN-sensors were straightforward to configure via CAN-USB adapter. In turn, configuration of the Wapice WRM247+ was not so straightforward due to the lack of support material. However, with help of the Wapice representative, the configuration succeeded.

4.2 Conveyor

The main conveyor of the Lokotrack is monitored by using vibration trending according to subsection 2.4.3. Vibration is trended in quite narrow band, because the interesting part of the frequency band, which is limited by natural frequencies of full and empty conveyor. The measurements were implemented as acceleration measurement, so the acceleration signal is converted to velocity according to the subsection 2.4.1. The acceleration signal is low-pass filtered before conversion and then the signal is integrated to velocity by using equation (7) and the RMS velocity is calculated by using equation (13). The RMS value is calculated over a measurement period of five seconds, and there is no interval between measurement periods. This is because the conveyor may begin to resonate between the measurement periods. The main conveyor RMS velocity of vibration is presented in Figure 18. The original measurement data can be seen in Appendix A.

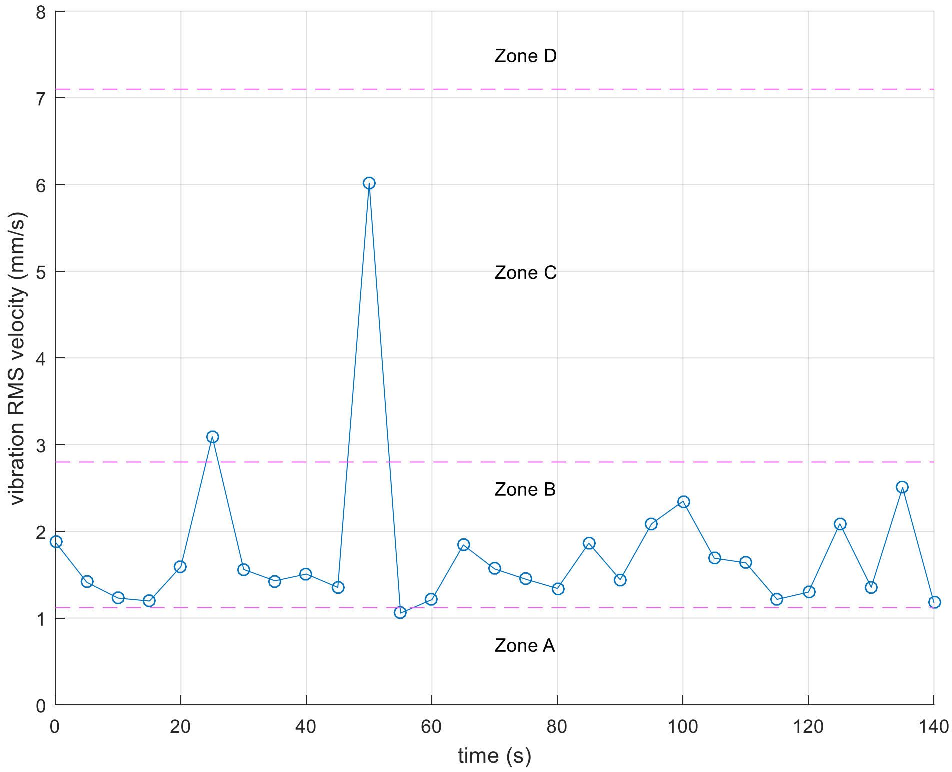

Figure 18. *Conveyor frame vibration RMS velocity at 2,50-4,67 Hz bandwidth.*

Figure 18 shows that the vibration RMS velocity remains relatively stable, but clearly visible higher values can be seen at times 25 seconds and 50 seconds. Higher single measurements values may be due to fact that there is momentarily higher mass on the conveyor and the swinging of the crusher causes excitation, which is damped when the conveyor natural frequency *returns to normal* after the growth of the instantaneous higher load.

The limits for the vibration zones is selected according to the SFS-ISO-10816, and the limits for class I machine group are used as an example. The limits for the zones are presented in Table 5.

Table 5. *Vibration RMS velocity limits for vibration zones.*

Zone	Vibration RMS velocity range (mm/s)
A	0…1,12
B	1,12…2.8
C	2,8…7,1
D	7,1…

The machine class I includes individual parts of the engines and machines, and the limits are the lowest ones in the classification.

4.3 Lokotrack frame

The Lokotrack frame orientation is calculated based on subsection 3.2.1 and by using equations (19) and (20). Before performing the measurements, there was no possibility to set the machine surely completely flat surface for sensor calibration, so the orientation before actual measurements are used as a reference orientation. Figure 19 presents the orientation of the Lokotrack in longitudinal direction during follow-up.

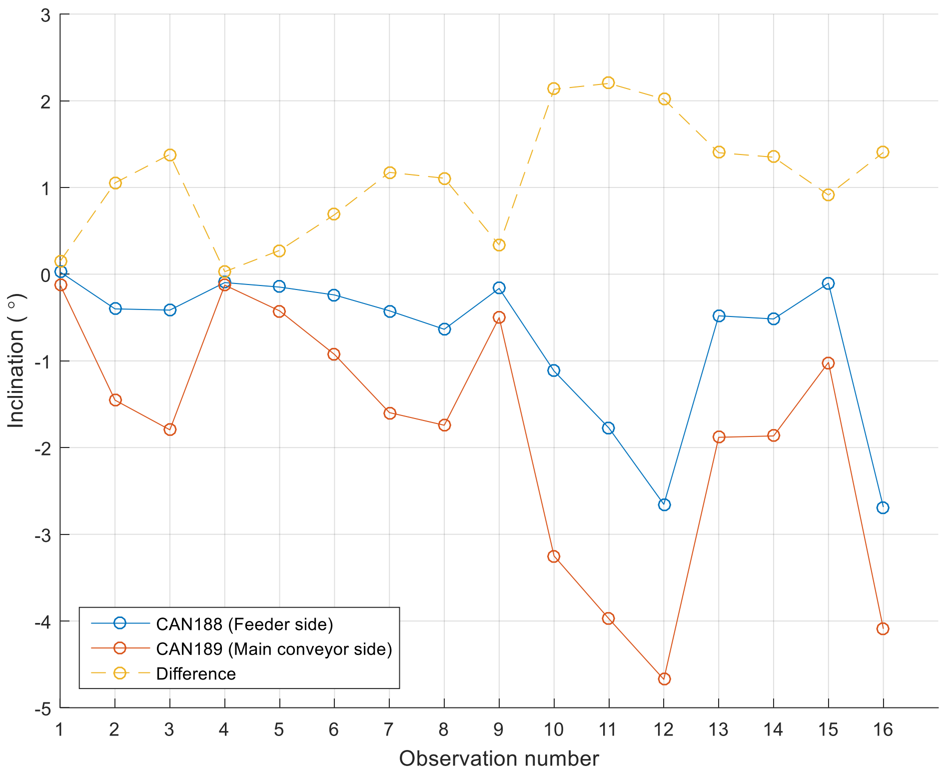

Figure 19. *Lokotrack orientation in longitudinal direction.*

Figure 19 reveals that inclination of the machine is likely greater than it is allowed to be. The limit in longitudinal direction is two degrees. Observations four and nine, for example, are interesting points, because they are likely made after the machine is moved and the orientation is checked. After both of those observations, the inclination in negative direction increases. This indicates that the feeder side of the machine goes down, which in turn, may be due to the heavy rocks that are dumbed in the feeder. In addition, the difference between measurement values in Figure 19 reveals that the frame is slightly twisted.

In turn, Figure 20 presents the orientation of the frame in lateral direction. Observation numbers are congruent with the Figure 19.

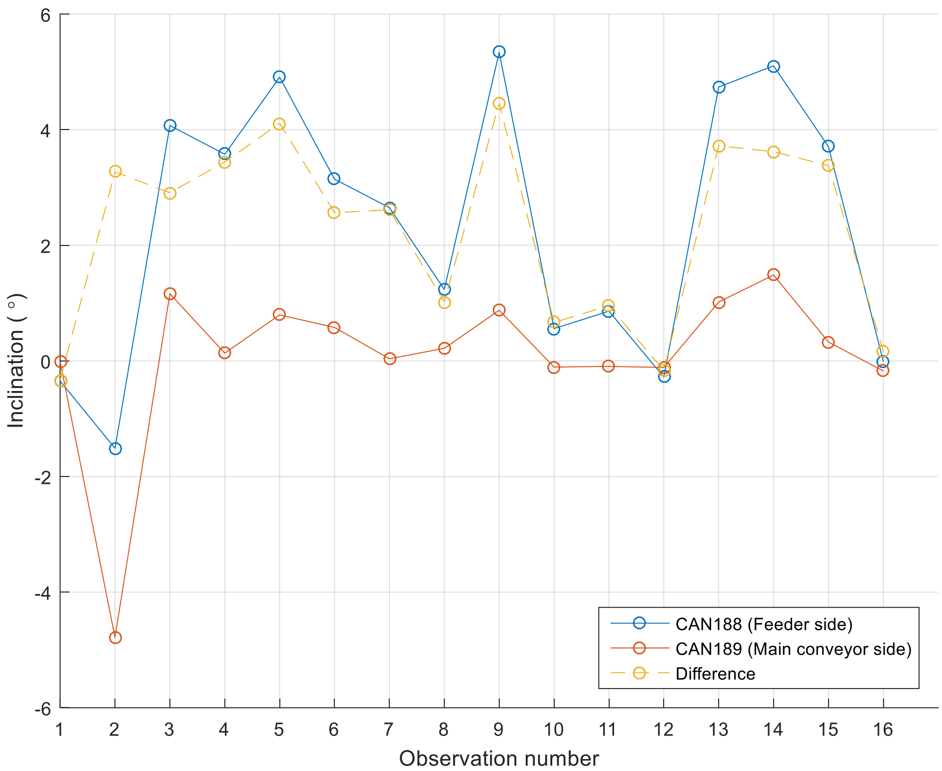

Figure 20. *Lokotrack orientation in lateral direction.*

It is notable in Figure 20 that the inclination of the main conveyor side stays relatively close to zero, if the observation number two is not noticed, but the feeder side of the inclination in lateral direction varies more. This is partly due to the I-beam structure of the frame. I-beam frame will twist relatively easily in longitudinal direction because of the roughness of the site surface. In this case, the longitudinal twist is when the axis, so to speak, around which the frame twists is longitudinal. If the base of the Lokotrack sinks at the feeder end, as Figure 19 shows, and the sinking is uneven and the change in inclination in feeder end of the machine will be higher than in main conveyor end. This is because of frame twists.

4.4 Crusher frame bearing

Bearing condition is usually evaluated by using several methods. In this work, the evaluation of the crusher condition is started by using vibration RMS velocity that is presented in subsections 2.4.1 and 2.4.3. Then the vibration spectrum that is presented in subsection 2.4.2 is used and then envelope analysis that is presented in subsection 2.4.4 is applied.

Before the evaluation, the dominating frequencies of single defects for different bearing components need to be calculated. The frequencies are calculated by using equations (9)-(11) and they are presented in Table 6. The dimensions and other parameters that are used in calculations are also presented.

Table 6. Bearing fault frequencies.

Fault	Frequency
Ball Pass Frequency of Outer race (BPFO)	58,84 Hz
Ball Pass Frequency of Inner race (BPFI)	72,46 Hz
Rolling element defect fault (REDF)	47,56 Hz
Cage unbalance (FTF)	2,26 Hz
Used dimensions and parameters: $f_r = 5{,}0500\ Hz$ $BD = 40{,}000\ mm$ $PD = 385{,}37\ mm$ $\beta = 8{,}8333°$ $n_b = 26\ (per\ row)$	

The evaluation of the crusher and crusher frame bearing is started by calculating the vibration RMS velocity. Standard ISO-10816-3 is applied to the measurement, so the vibration RMS velocity is calculated between 2-1000 Hz [51]. The RMS velocity in vertical direction is $1{,}9121\ ^{mm}/_{s}$ and in horizontal direction $6{,}9310\ ^{mm}/_{s}$. According to these results, the horizontal direction needs further investigation, because the value is over the acceptable zone for long-term use.

The vibration acceleration spectra of 0-150 Hz frequency band is presented in Figure 21. The original measurement data can be seen in Appendix A.

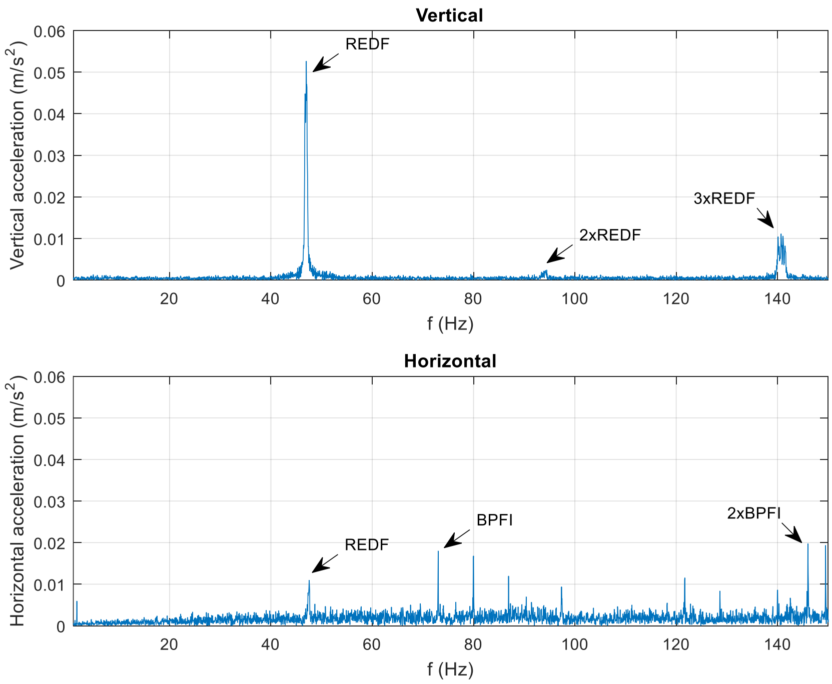

Figure 21. *Vibration acceleration spectrum of bandwidth 0-150 Hz.*

Figure 21 shows significant peak at rolling element defect frequency in vertical direction spectrum, if the peak is compared to carpet level of the spectrum. In addition, the REDF has also two multiples. In horizontal direction spectrum, the REDF peak is smaller than in vertical direction signal. Instead, there are peaks at BPFI and at its second harmonic. It is notable to that amplitudes at frequencies around rotational frequency of the crusher are relatively low when compared the observations above.

Envelope analysis is the last method for evaluation of the crusher, and especially of a frame bearing, condition. The suitable pass band for envelope analysis is estimated by using Table 2 and wideband frequency spectrum of acceleration. The wideband spectrum is presented in Appendix B. The wideband frequencies have few peaks and bands at where the signal amplitude is increased. These bands are potential pass bands for envelope analysis. The selected passband is 1600 Hz band that is centered at 4250 Hz. Other investigated center points were 500 Hz and 1000 Hz. Hammer test of the bearing housing was excluded, because that would damage the paint surface of the crusher, which protects the housing from corrosion. The frequency spectra of the envelope analysis are presented in Figure 22.

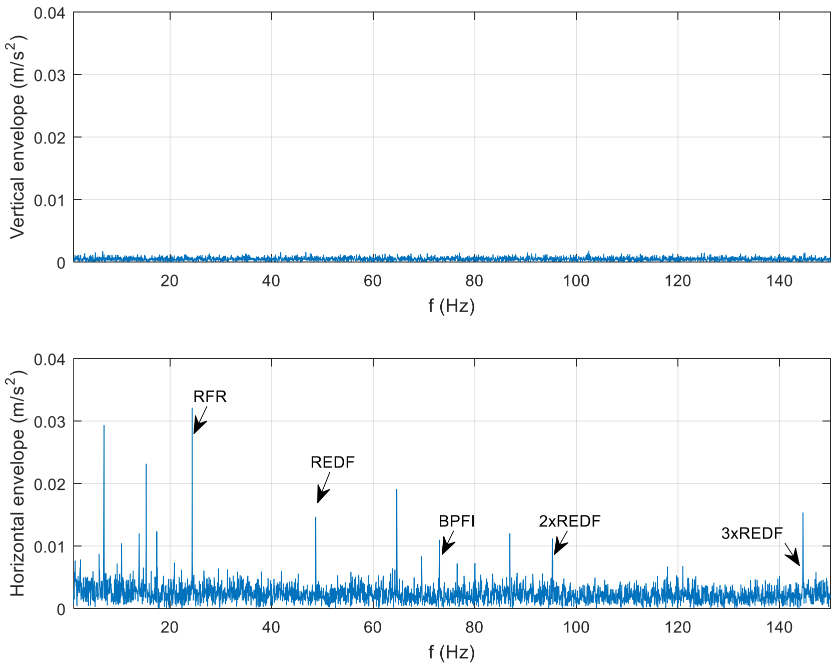

Figure 22. *Frequency spectra of envelope.*

In vertical direction, the envelope does not reveal any faults, but in horizontal direction, few spikes in envelope spectrum that there may occur few early stage faults. The detectable single faults from Figure 22 are rolling element fault and inner race fault. It is notable that REDF has also two multiples, which may indicate that the fault is slightly severe than inner race fault. Without evaluating the remaining lifetime of the bearing, the faults are started to develop, because of the mechanical impacts that are shown in envelope spectrum.

4.5 Wireless sensors at crushing plant

This subsection presents results related to the wireless measurements. The results are differentiated to its own subsection, because the wireless measurements caused problems during measurements. Pre-testing at the test site gave expectations for reasonable reception, but in the actual experiment, the measurements are not as successful as hoped.

Due to unsuccessful measurements with wireless sensors, comparative measurements with wired sensors for conveyor frame or Lokotrack frame proved to be unsuccessful too. This is most likely due to poor reception of the BLE signal in site conditions. Figure 23 presents histogram of sample intervals. The intervals between measurement samples are calculated from the timestamps that are recorded to the measurement data file.

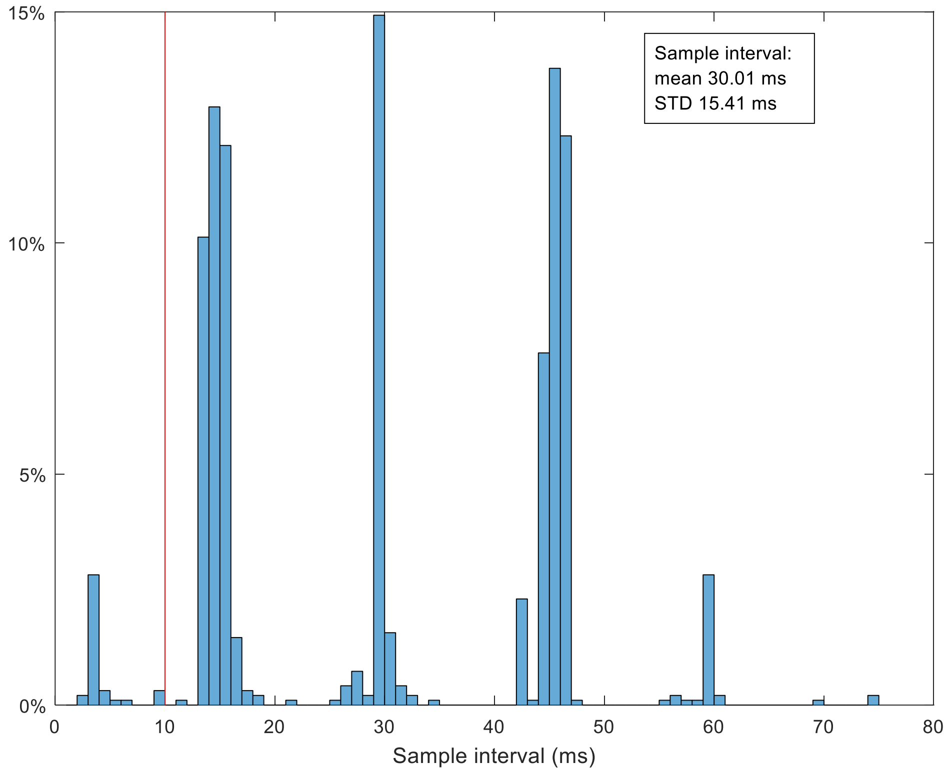

Figure 23. *Histogram of sample interval of TI Sensor Tags based on measurement data timestamps.*

As can be seen from Figure 23, the measurement interval in recorded data is most likely around 15, 30 and 45 milliseconds. The number of packets transmitted is not validated, but most likely the packets are lost due to poor reception. The result can be read so that when the sample interval has been around 30 ms, every other packet has lost, and when the sample interval is around 45 ms, only every third packet has received.

4.6 Vibration sensor features

This subsection evaluates the used sensors in technical and financial point of view. In addition, it is also assessed how well the sensors performed in site conditions. Table 7 compiles the technical and financial features of the sensors that has been reported in datasheets for at least two sensors.

Table 7. *Technical and financial comparison of the used sensors.*

	IFM VSA001 [30]	**Proemion ACC3501 [44]**	**MSP (TI Sensor Tag CC2650) [28] [29]**
Measurement frequency	Max. 6000 Hz (*)	Max. Output 100 Hz Internally 1000 Hz	Internally max 4000 Hz
Measurement axis	1	3	3
Measurement range	±25g	±50g	Max. ±16g
Housing	IP68	IP67	-
Operating voltage	7,2…10,8 VDC	9…36 VDC	3 VDC Battery
Operating temperature	-30…125 °C	-20…85 °C	-40…85 °C
Sensitivity	0,2 mg/√Hz	-	0,3 mg/√Hz
Communica-tion	Analog current out-put (0…10 mA)	CANopen	BLE
Connection	M12 4-pin	M12 4-pin	Wireless
Accessories	VSE002 diagnostic electronics	-	Bluetooth gateway required
Sensor price	~150€	~500€	29$
Notes: (*) The measurement range that is given in datasheet, is frequency range that can be measured, not measurement frequency.			

In technical point of view, the measurement and temperature ranges are sufficient to crushing plant applications. The housing IP-rating of the wired sensors are also sufficient. TI Sensor Tag is not IP-rated, but the situation can be improved with better housing. For example, demo enclosure presented in Figure 4 remained water and dust proof. Figure 24 shows why the enclosure demands are important. The pictures were taken two months after installation.

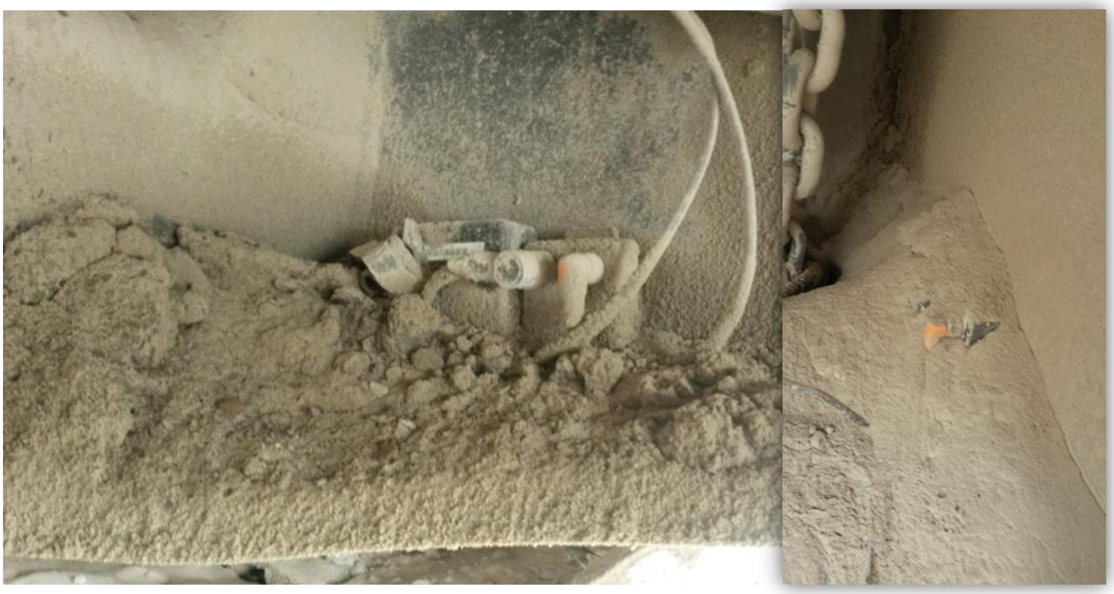

Figure 24. *Sensors on Lokotrack frame two months after installation. On the left is the sensors in main conveyor side and on the right side presents the feeder side sensors.*

If Figure 24 is compared to Figure 15 and Figure 16, where the sensors are newly installed, the operating circumstances require a lot from the enclosure. It is also notable that there are abnormally low water or ice in Figure 24 if the climate at the test site area is taken into account.

Operating voltages of the sensors may cause concerns. Lokotracks includes 24 VDC electricity system, so the IFM VSA001 sensors needs voltage converter, but the Proemion ACC3501 can use 24 VDC directly. In turn, the concern with wireless sensors is battery life. In this work, the office quality AA alkaline battery life was around six weeks. There was no built-in optimized current consumption in the sensors, but the sensors were advertising themselves constantly between measurements. That increases the power consumption.

Communication of the sensors and other devices that the used sensors require, are also important to assess. IFM VSA001 sensors communicates via analog current signal, and the most straightforward method to analyse the signal is to use IFM diagnostic electronics. The diagnostic electronics communicates via Ethernet/IP and it is basically meant to use with IFM monitoring software. Proemion ACC3501 communicates via CAN bus, so it is easy to connect to CAN bus of the machine without extra devices for the communication. Instead, BLE sensors require Bluetooth gateway that collects the data from the sensors.

In financial point of view, if the possible development work of hardware or software is not taken into account, the payback period of a single sensor is relatively short, if the estimation from the subsection 1.1 is taken into account. According to the estimation, eight hour of lost production causes more than 20000€ lost income.

5. DISCUSSION

This subsection answers to the research questions that are presented in subsection 1.3 according to the results presented in section 4. In addition, the results are explained in more detail and they critically evaluated.

The research question number one asks what kind of phenomena can be monitored from the machine by measurements. According to the results in section 4, the measuring of Lokotrack orientation gives the most potential results. The experiment reveals that due to unevenness of the surface, the Lokotrack frame is almost always twisted while the machine is used, and the inclination of the machine is not always monitored except when the machine is moved. In addition, the spirit levels that are located in the control cabinet, do not necessarily detect the inclination or twist of the frame, because the inclination is measured only at one point. As inclination measurement in lateral direction of the Lokotrack shows in Figure 20, the inclination stays relatively close to zero level in main conveyor side of the machine. At the same time, the measured inclination may vary several degrees. This is possible, because the I-beam structure of the frame is not rotationally rigid. This allows, for example, that the corner of the Lokotrack frame opposite to the measurement point sinks without being detected. Metso have developed a system that compensates some of the inclination of the C-jaw crusher, but the crossing of the maximum compensation is could not be detected.

Furthermore, inclination may affect other devices also. For example, screens and conveyors are also inclined, if the frame is inclined or twisted. This may cause rotational vibration to conveyors, which have also I-beam structure. This causes energy loss and additional mechanical stress as well in screens as in conveyors. In addition, lack of proper inclination information of the machine, the faults that may be caused by excessive twist or inclination are not detected, so that will cause premature failure, and so warranty costs to Metso or the customer.

In order to improve the Lokotrack frame related experiment, the measurements could be made by using gyroscope-based sensor. However, the justification for the accelerometer, however, is that the versatility and potential of the acceleration measurements are interesting. Other improvement, if the severity of the inclination and twist is evaluated, the sensors need to be calibrated with Lokotrack that are on factory floor. In this work, the calibration measurements were taken at the site.

Relating to the research question number one, the measurements of the crusher frame bearing give also interesting results. Vibration RMS velocity of the horizontal direction gives rise to suspicion of a possible fault. In addition, envelope analysis of the horizontal measurement signal suggests also that there may be beginning fault in a single rolling element and possibly also on inner race of the bearing. The severity of the faults are difficult to evaluate, but when there is a peak in the envelope, that means that developing fault occurs, which may develop rapidly. The envelope of the vertical direction measurement is also interesting, because there are no signs of failures.

One potential explanation of smooth spectrum of the vertical direction envelope may be positioning of the sensor. The sensor is located on the top of the bearing housing, so when the resultant of the forces or stresses are not pointed to the upper section of bearing housing, the impacts may be damped. If the vertical acceleration is measured at the bottom of the housing, the envelope may detect the same faults than the envelope analysis of horizontal measurement. In addition, rigid screw mounting should be tested instead of magnet mounting. Another thing, and maybe the most important thing to develop in bearing condition measurement experiment, is that the monitored time period should have been longer, and on the other hand, there is no measurement data of that specific bearing when it was new, so that acceleration spectrum could have been compared to current vibration spectrum. Furthermore, the detected failure symptoms with vertical direction envelope cannot be confirmed, because it was not possible to remove the bearing and investigate it closer.

The results related to the vibration measurement of main conveyor gives also answers to the research question number one. Vibration or swinging of the main conveyors due to resonance are rare issue, because the natural frequencies of the main devices of a Lokotracks are modeled and designed accurately. Instead, possible side conveyors are more sensitive the emergence of resonance. In cases where the conveyor frame is cracked, the conveyor had been in resonance before the breakdown. These kind of situations are extremely dangerous for operators, and on the other hand, the fixing of the conveyor frame can be very time consuming. The increase in vibration level can also reveal other kind of faults related to conveyor, such as loosening of conveyors stays. The approach to the measurement of conveyor vibration can be improved, for example, by measuring torsional vibration. On the other hand, the measurement setup that is used in this work covers the main direction at where the motion of the crusher jaw may excite the vibration. In addition, the sensor installation point in this experiment was on the edge of the conveyor, so the torsional vibration would be one component of the measured vibration. Although, that component cannot be recognized from the signal.

Concerning the research question number two, which asks the minimum requirements for the implemented measurements. The measurement frequency in experiments related to Lokotrack frame and conveyor is too high. One-second sampling interval may be sufficient for the inclination, if the inclination measurement is executed to check the inclination before the machine is started. In case of the conveyor vibration measurement, the minimum measurement frequency may be reduced to around 50 Hz. With that measurement frequency, the shape of the highest frequency of the monitored frequency band, which is 4,67 Hz, can still be detected. In case of the crusher and its frame bearing monitoring, the requirements depend on the data-analysis methods. If only the vibration RMS velocity is monitored and the maximum of the measured frequency band is 1000 Hz, the used measurement frequency may be a bit lower than with more developed methods. For envelope analysis, the used instruments are close to the minimum. The common requirement for all measurement devices are sufficient enclosure and wide enough operating temperature range, which is fulfilled according to the results in subsection 4.6.

The research question number three considers the economic feasibility of these measurements. The unit cost of one sensor and required additional equipment are pretty high considering that, for example, Lokotracks are series-products and thus the manufacturing costs of the machine are important to control. The economic feasibility should be looked at the whole machine level. The condition monitoring system should be implemented so that the most critical process devices and most frequent failures are covered. It also affects the price of the system that is it desired to know the exact fault, or is it sufficient to know that something is wrong. If only the measurements that are implemented in this work and their criticality in relation to the unit price of the sensor are observed, the measurement of Lokotrack orientation may be the most feasible. By preventing the customer to misuse the machine (excessive inclination or twist), the lifecycle of the machine may increase. The condition monitoring of the crusher bearing, and other bearings and shafts of the main process devices, are the second one. This is because those parts are moving and wearing parts, and they are important for process operation. In economic sense, the conveyor monitoring may not be feasible with the used measurement setup, because the conveyor resonance is really rare. Because the payback time is one of the most important things to the customer, the feasibility may increase, if the measurements can be implemented with cheaper sensors.

In this work, TI Sensor Tags represented these cheaper sensors. However, the wireless measurements are unsuccessful in this work. The main reason for this is probably bad reception of the BLE signal. Two potential main reasons for the poor reception are heavy steel structures of the Lokotrack and poorly performing antennas of the TI Sensor Tags and Raspberry PI 3. Heavy steel structures block the signals and some of the signals reach their destination only through reflections. Both TI Sensor Tags and Raspberry PI 3 have Bluetooth antennas that are integrated in the circuit board. External antennas may improve the reception.

In addition to the hardware issues of the wireless sensors, the software needs also improvements. The results, related to the wireless measurement in subsection 4.5, also give an indication that the sensors must contain more intelligence than the sensors used in this work contain. In addition to the poor reception, the data transmission capacity of BLE is insufficient (the theoretical minimum time of one transaction is 7,5 ms [52]) and the current consumption is too high if high-frequency measurement data is transferred constantly. The battery life should be at least two years in these kind of applications.

6. CONCLUSION

Following subchapters consider conclusions that can be made based on the results of this work, and suggest potential future work with condition monitoring for crushing plants and measurements that are presented in this work as well. When reviewing the results of this work, it should be noted that the experiment was limited only single machine and application specific solutions. Different types of machines and plants may have different needs, and monitoring of many other components that are not so applications specific, may have higher priority, when CMS is developed.

6.1 Conclusions

Increasing competition and decrease of commodity prices have put pressure to improve the efficiency of production and to reduce of production costs in field of mineral and aggregate industry. In addition, service business has become an increasingly important part of the business of many equipment manufacturers. Different kind of remote monitoring systems have been developed so that customer can monitor and develop their processes. Condition monitoring offers a great improvement for situational awareness, which in one important key in development of processes.

Condition monitoring enables proactive maintenance instead of reactive or maintenance based on fixed time intervals. CMS improves the uptime of the plant, because unexpected failures and be avoided, and maintenance can be executed well scheduled and based on machine condition. In this way, process stops can be scheduled, the spare parts can be delivered to the site before the process is shut down, and multiple service tasks can be done in one process stop.

However, it is not indifferent how the implementation of condition monitoring is started. At the beginning of the implementation, the criticality of all process devices need to be obtained. That knowledge can be used for defining of the requirements for CMS. Main points of the requirements are, for example, that is an online monitoring system needed or is a periodic manual measuring sufficient, or how early detection of defects are desired and how the data is present to user. In many cases, the price of the CMS is also important.

The selected measurement and data-analysis methods have a great influence to the price of CMS. In many cases, such as in vibration measurements, early stage fault detection requires higher sampling rate, more expensive measurement devices and maybe even a person to investigate the results. In other hand, for instance, magnetic plug in the oil tank or point-form temperature measurement of a bearing may prevent total breakdowns, but they do not give possibility to predict the failures and plan the maintenance schedule.

In this work, the goal of this thesis was to find potential condition monitoring applications for crushing plants. The implemented application specific condition monitoring methods were orientation of a Lokotrack, vibration of conveyor and vibration measurements of crusher frame bearing. In addition, the first two of those measurements were implemented also with wireless sensors. These measurements were selected according to the criteria that are presented in Table 3. The results of this work showed that measuring of the Lokotrack orientation varies during use, and it is difficult to set according to the strict inclination limits. The results also proved that the orientation need to be measured from several points, because elastic I-beam structure may be quite a lot twisted, which may cause adverse effects to the crusher, and other actuators. The crusher frame bearing related measurements gave indications of early stage faults in the bearing. However, this could not be verified, but it will be near future task to monitor and verify results when the bearing is replaced. The unsuccessful measurements gave valuable information about the requirements that this kind of application sets to the sensors and data transmission. The most important observations were the challenges brought by the machine structures, and that the sensors need to be intelligent enough so that raw data does not need to be transferred constantly. The next chapter provides suggestions how these results can be used and developed in the future.

6.2 Future work

This subsection presents proposals how to proceed in future. Due to increasing demand of situational awareness of the processes the most important proposal is to develop commercial crushing plant CMS. Developing of the condition monitoring system should start according to the subchapter 2.2.7, and experience of the maintenance organization should be utilized when failure modes are considered.

The results and working during the research aroused a lot of ideas how the work can be continued, and how the results could be utilized. Lokotrack frame inclination measurement revealed that spirit levels are insufficient for detecting the frame orientation, because the current solution does not warn the user if the orientation changes. In turn, the current solution measures the inclination angles only in one point and the twist of the frame is not detected. Twisted or too inclined frame may cause harmful forces to crusher, tilt of screens may be incorrect and material in screens or conveyors may distribute unevenly. If the orientation of a Lokotrack is desired to be monitored during process is running, the measurement should be implemented so that vibration is compensated as subchapter 2.4.5 suggests.

The use of wireless sensors require solutions that solve problems relating to signal reception and data transmission. Crushing sites are harsh environments for wireless network due to the heavy steel structures, so the sensors need better antennas, some built-in intelligence and placement of sensor gateways should be planned carefully as well. For example, data buffering enables higher measurement frequency with slower data transfer, data pre-processing or simple analysis decreases the amount of transferred data and optimized power consumption increases battery replacement interval.

Another future idea is that the condition monitoring system needs an interface to IC system. IC may offer measurement data such as rotational speeds and CMS can send warning or alarm to IC if evolving defect is detected. Useful measurements implemented in this work for protecting the machine, are Lokotrack frame orientation and conveyor frame measurements. The orientation measurement of the Lokotrack is also needed, if the movements of the machine is wanted to automate in the future.

The potential of CMS should be evaluated broader in Metso products, condition monitoring is likely to be also profitable in other aggregate and mining machines, such as large conveyor systems. In large conveyor systems, the material flow depends on the fact that conveyors are in good condition. Even minor issue could has major consequences. For example, one failed conveyor roller is not a major issue, but if the failure of that roller is not detected, eventually the failed roller may destroy an expensive conveyor belt.

REFERENCES

[1] European Aggregates Association (UEPG), "Annual Review 2014-2015," 2015. [Online]. Available: http://www.uepg.eu/uploads/Modules/Publications/uepg-ar2014-2015_210x297mm_v18_pbp_small.pdf. [Accessed 29 2 2016].

[2] K. Viilo, Crushing and Screening Handbook, 5th ed., Tampere: Metso Minerals, 2011.

[3] E. Kaaja, Factory's warranty costs current state. Master of Science Thesis, Tampere: Tampere University of Technology, 2016.

[4] SKF, "SKF integrated Condition Monitoring Brochure," 2016. [Online]. Available: http://www.skf.com/binary/21-75560/11951-ICM_Brochure_05Jan16-single.pdf. [Accessed 3 3 2016].

[5] Metso Minerals, "ScreenWatch Brochure," 2014. [Online]. Available: http://www.metso.com/miningandconstruction/MaTobox7.nsf/DocsByID/C08BEA5B3BD34B8585257D38005EA3C0/$File/ScreenWatch_Screen_Monitoring_2014_LR.pdf. [Accessed 3 3 2016].

[6] Valmet, "Condition monitoring with Valmet DNA," 2016. [Online]. Available: http://www.valmet.com/products/automation/valmet-dna-dcs/condition-monitoring/. [Accessed 3 3 2016].

[7] SFS-ISO 5348, Mechanical vibration and shock. Mechanical mounting of acceleroemters., 2012.

[8] SFS-ISO 7919-1, Mechanical vibration of non-reciprocating machines. Measurements on rotating shafts and evaluation criteria. Part 1: General guidelines, 2012.

[9] SFS-ISO 13373-1, Condition monitoring and diagnostic of machines - Vibration condition monitoring - Part 1: General procedures, 2012.

[10] SFS-ISO 13379-1: Condition monitoring and diagnostics of mahcines. Data interpretation and diagnostics techinques. Part 1: General guidelines, 2012.

[11] SFS-ISO 10816-1, Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts - Part 1: General guidelines, 2012.

[12] SFS-ISO 10817-1, Rotating shaft vibration measuring systems. - Part 1: Relative and absolute sensing of radial vibration, 2012.

[13] SFS-ISO 18434-1, Condition monitoring and diagnostics of machines. Thermography. Part 1: General procedures, 2011.

[14] W. Qiao and L. D, "A Survey on Wind Turbine Condition Monitoring and Fault Diagnostics - Part I: Components and Subsystems," *IEEE Transactions on Industrial Electronics,* vol. 62, no. 10, pp. 6536-6545, 2015.

[15] W. Qiao and D. Lu, "A Survey on Wind Turbine Condition Monitoring and Fault Diagnosis - Part II: Signals and Signal Processing Methods," *IEEE Transactions on Industrial Electornics,* vol. 62, no. 10, pp. 6546-6557, 2015.

[16] Y. Peng, "Intelligent condition monitoring using fuzzy inductive learning," *Journal of Intelligent Manufacturing,* no. 15, pp. 373-380, 2004.

[17] P. Li, J. Eickmeyer and O. Niggemann, "Data Driven Condition Monitoring of Wind Power Plants Using Cluster Analysis," in *International COnference on Cyber-Enabled Distributed Computing and Knowledge Discovery*, 2015.

[18] J. Nurmi, J. Honkakorpi, V. Juho and J. Mattila, "Micro-electromechanical System Sensors in Unscented Kalman Filter-based Condition Monitoring of Hydraulic Systems," in *2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, Wollongong, 2013.

[19] R. G. Cooper, "State-Gate systems: A new tool for managing new products," *Business Horizons*, vol. 33, no. 3, pp. 44-54, 1990.

[20] A. G. Piersol and T. L. Paez, Harri' Shock and Vibration Handbook, Sixth Edition, McGraw-Hill Professional, 2010.

[21] SFS-ISO 2041, Mechanical vibration, shock and condition monitoring. Vocabulary, 2011.

[22] L. Wang and R. X. Gao, Condition Monitoring and Control for Intelligent Manufacturing, London: Spinger-Verlag, 2006.

[23] P. Tavner, L. Ran, J. Penman and H. Sedding, Condition Monitoring of Rotating Electrical Machines, London: The Institution of Engineering and Technology, 2008.

[24] A. Hughes, B. Drury and W. Drury, Electric Motors and Drives, 4th ed, London: Elsevier, Inc., 2013.

[25] R. Tiainen, J. Särkijärvi, J. Ahola and T. Lindth, "Utilization Possibilities of Frequency Converter in Electric Motor Diagnostics," in *International Symposium on Power Electronics, Electrical Drives, Automation and Motion, 2006. SPEEDAM 2006.*, Taormina, Italy, 2006.

[26] O. Duque, M. Perez and D. Morinigo, "Detection of Bearing Faults in Cage Induction Motors Fed by Frequency Converter using Spectral Analysis of Line Current," in *IEEE International Conference on Electric Machines and Drives*, San Antonio, USA, 2005.

[27] J. P. Bentley, Principles of Measurement Systems, 4th edition, Harlow, England: Pearson Education, 2005.

[28] Texas Instuments, "Multi-Standard CC2650 SensorTag Design Guide," March 2015. [Online]. Available: http://www.ti.com/lit/ug/tidu862/tidu862.pdf. [Accessed 16 June 2016].

[29] IvenSense, "MPU-9250 Product Specification Revision 1.0," 17 January 2014. [Online]. Available: https://www.invensense.com/wp-content/uploads/2015/02/MPU-9250-Datasheet.pdf. [Accessed 17 June 2016].

[30] IFM-electronic, "VSA001 Vibration sensor," 8 October 2015. [Online]. Available: http://tds.ifm-electronic.com/tentacle/us/VSA001.pdf. [Accessed 16 June 2016].

[31] Proemion / RM Michaelides software & Elektronik, "Hard- /Firmware Manual RM CANsense ACC," Fulda, 2010.

[32] SFS-ISO 13373-2, Condition monitoring and diagnostic of machines. Vibration condition monitoring. Part 2: Processing, analysis and presentation of vibration data, 2012.

[33] E. Chu, Discrete and Continuous Fourier Transforms : Analysis, Applications and Fast Algorithms, Chapman and Hall/CRC, 2008.

[34] Mathworks Inc., "Documentation: discrete Fourier transform," [Online]. Available: http://se.mathworks.com/help/matlab/math/discrete-fourier-transform-dft.html. [Accessed 3 September 2016].

[35] Mathworks Inc., "Documentation: fast Fourier transform," [Online]. Available: http://se.mathworks.com/help/matlab/ref/fft.html#buuutyt-6. [Accessed 3 Septemper 2016].

[36] M. J. S. lawrence, "Computing the Discrete-Time "Analytic" signal via FFT," *IEEE Transactions on Signal Processing*, vol. 47, no. 9, pp. 2600-2603, 1999.

[38] SFS-ISO 13373-3, Condition monitoring and diagnostics of machines -- Vibration condition monitoring -- Part 3: Guidelines for vibration diagnosis, 2015.

[39] ABB OY, ABB TTT-käsikirja 2007. Kunnonvalvonta ja huolto, 2000.

[40] SKF, "Note CM3024: Acceleration Enveloping in Paper machines," SKF Reliability Systems, San Diego, 2000.

[41] T. Barszcz and A. Jablonski, "A novel method for the optimal band selection for vibration signal demodulation and comparison with the Kurtogram," *Mechanical Systems and Signal Processing,* vol. 25, no. 1, pp. 431-451, 2011.

[42] R. E. Moyer and J. P. The late Frank Ayres, Schaum's Outline of Trigonometry, Fifth Edition, New York, Chicago, San Francisco, Lisbon, London, Madrid, Mexico City, Milan, New Delhi, San Juan, Seoul, Singapore, Sydney, Toronto: McGraw-Hill, 2013.

[43] Metso Minerals Oy, "Metso LT106 Brochure," 2015. [Online]. Available: http://www.metso.com/miningandconstruction/MaTobox7.nsf/DocsByID/BB3A5829D48BE3CDC22579A300349CAB/$File/Lokotrack-LT106-mobile-jaw-crushing-plant.pdf. [Accessed 12 Aug 2016].

[44] Proemion, "CANsense ACC series datasheet," - - 2015. [Online]. Available: https://proemion.com/files/Downloads/datasheets_datenblaetter/2015/en/DS_rm-cs_acc_V2-0_en.pdf. [Accessed 2 August 2016].

[45] IFM Electronics, "VSE001 Diagnostic electronics datasheet," 19 November 2007. [Online]. Available: http://tds.ifm-electronic.com/tentacle/ind/VSE001.pdf. [Accessed 2 August 2016].

[46] Raspberry PI Foundation, "Raspberry PI 3 Model B," [Online]. Available: https://www.raspberrypi.org/products/raspberry-pi-3-model-b/. [Accessed 2 August 2016].

[47] Secomea, "Sitemanager 1139 and 3339 datasheet," 16 May 2015. [Online]. Available: http://secomea.com/wp-content/uploads/2015/08/SiteManager_1139-3339.pdf. [Accessed 2 August 2016].

[48] Moxa, "EDS-P206A-4PoE Series datasheet," 15 April 2016. [Online]. Available: http://www.moxa.com/doc/specs/EDS-P206A-4PoE_Series.pdf. [Accessed 2 August 2016].

[49] Wapice Oy, "WRM 247+ datasheet," - - 2015. [Online]. Available: https://www.iot-ticket.com/images/Files/WRM247+_DataSheet_2015.pdf. [Accessed 2 August 2016].

[50] Wapice Oy, "IoT-Ticket.com, Your ticket to the Internet of Things and beyond," [Online]. Available: https://www.wapice.com/products/iot-ticket-internet-of-things-platform. [Accessed 19 Aug 2016].

[51] SFS-ISO 10816-3: Mechanical vibration — Evaluation of machine vibration by measurements on non-rotating parts — Part 3: Industrial machines with nominal power above 15 kW and nominal speeds between 120 r/min and 15 000 r/min when measured in situ, 2009.

[52] Bluetooth SIG, Inc., "What is Bluetooth technology," 2016. [Online]. Available: https://www.bluetooth.com/what-is-bluetooth-technology. [Accessed 27 June 2016].

[53] W. Zhou, T. G. Habetler and R. G. Harley, "Bearing Condition Monitoring Methods for Electric Machines: A General Review," Georgia Institute of Technology, Atlanta, 2007.

[54] Y. Cao, X. Rong, S. Shao and K. He, "Present situation and prospects of vibration sensors," in *2012 International Conference on Computer Distriputed Control and Intelligent Environmental Monitoring*, Hunan, 2012.

[55] SFS-ISO 10816-6, Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts - Part 6: Reciprocating machines with power ratings above 100 kW, 2013.

[56] Mathworks Inc., "Documentation: resample," [Online]. Available: http://se.mathworks.com/help/signal/ref/resample.html. [Accessed 31 August 2016].

[57] F. K. Geitner and H. P. Bloch, Machinery Failure Analysis and Troubleshooting (Fourth Edition), Oxford: Butterworth-Heinemann, 2012.

APPENDIX A

Original data of crusher and conveyor related measurement are presented in this appendix. The data related to Lokotrack frame is not presented, because 42 different datasets are not sensible to present.

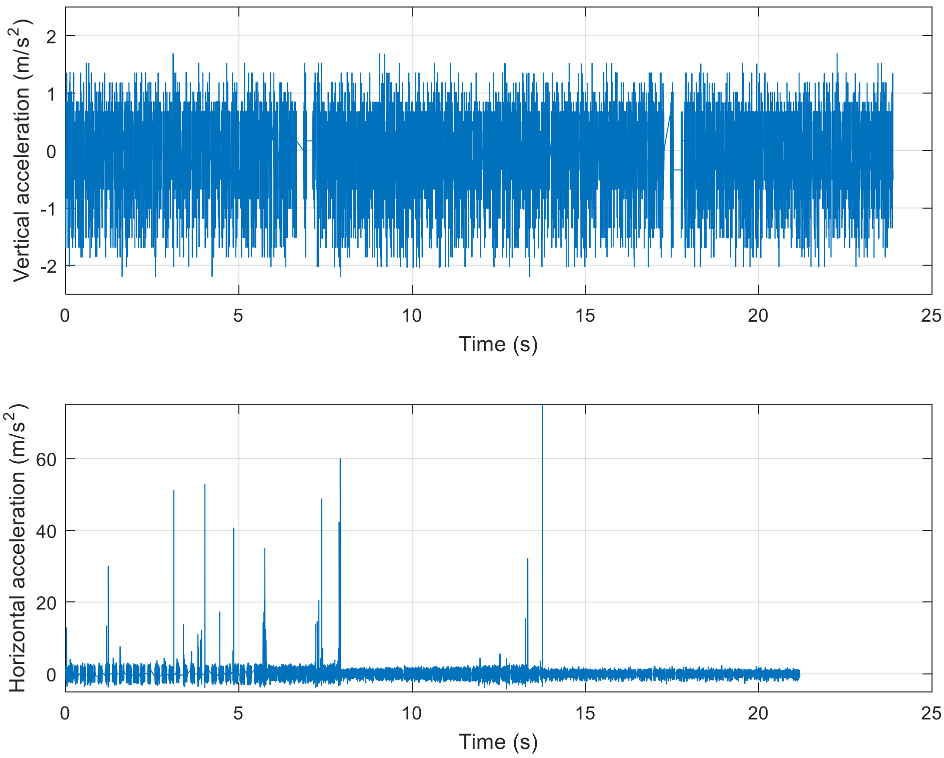

Figure 1. *Original acceleration data of the Lokotrack frame bearing.*

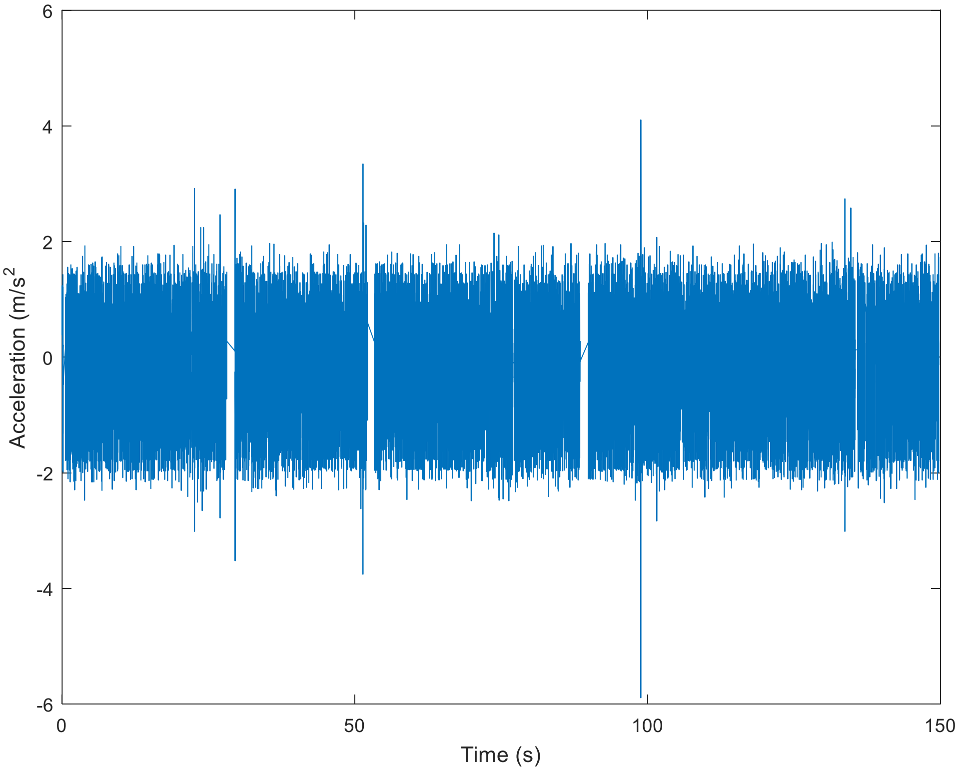

Figure 2. *Original data that are measured from the conveyor during process is running.*

APPENDIX B

This appendix presents the wideband frequency spectrum of the crusher related measurement. The spectrum is used to estimate the suitable pass band for envelope analysis.

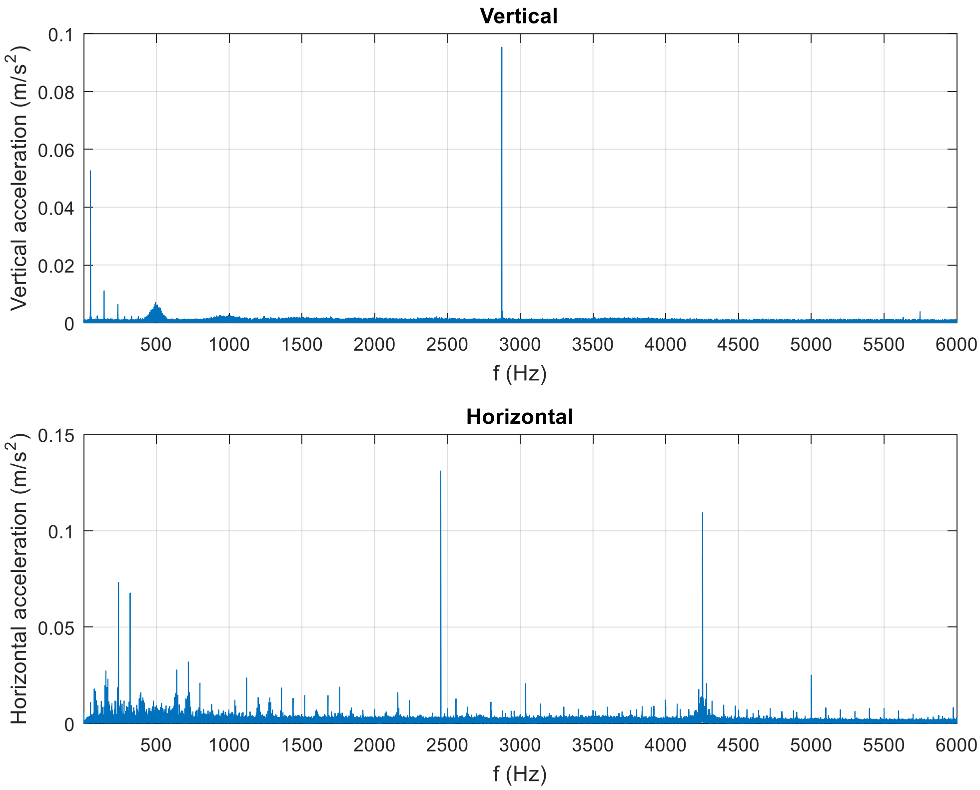

Figure 1. *Vibration acceleration spectrum of bandwidth 0-6000 Hz.*